BLANK OPTIMIZATION IN SHEET METAL FORMING USING FINITE ELEMENT SIMULATION

A Thesis

by

AMIT GOEL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Mechanical Engineering

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Approved as to style and content by:

Jyhwen Wang (Chair of Committee)	Karl Hartwig (Member)
Yu Ding (Member)	Dennis O'Neal (Head of Department)

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ABSTRACT

Blank Optimization in Sheet Metal Forming Using

Finite Element Simulation. (December 2004)

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Chair of Advisory Committee: Dr. Jyhwen Wang

The present study aims to determine the optimum blank shape design for the deep drawing of arbitrary shaped cups with a uniform trimming allowance at the flange i.e. cups without ears. This earing defect is caused by planar anisotropy in the sheet and the friction between the blank and punch/die. In this research, a new method for optimum blank shape design using finite element analysis has been proposed. Explicit non-linear finite element (FE) code LSDYNA is used to simulate the deep drawing process. FE models are constructed incorporating the exact physical conditions of the process such as tooling design like die profile radius, punch corner radius, etc., material used, coefficient of friction, punch speed and blank holder force. The material used for the analysis is mild steel. A quantitative error metric called shape error is defined to measure the amount of earing and to compare the deformed shape and target shape set for each stage of the analysis. This error metric is then used to decide whether the blank needs to be modified or not. The cycle is repeated until the converged results are achieved. This iterative design process leads to optimal blank shape. In order to verify the proposed method, examples of square cup and cylindrical cup have been investigated. In every case converged results are achieved after a few iterations. So through the investigation the proposed systematic method of optimal blank design is found to be very effective in the deep drawing process and can be further applied to other stamping applications.

To my grandfather and his love

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First and foremost I thank GOD, the Generous, for having finally made this humble effort a reality.

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CHAPTER I

INTRODUCTION

Sheet metal forming is one of the most widely used manufacturing processes for the fabrication of a wide range of products in many industries. The reason behind sheet metal forming gaining a lot of attention in modern technology is due to the ease with which metal may be formed into useful shapes by plastic deformation processes in which the volume and mass of the metal are conserved and metal is displaced from one location to another [1]. Deep drawing is one of the extensively used sheet metal forming processes in the industries to have mass production of cup shaped components in a very short time. In deep drawing, a flat blank of sheet metal is shaped by the action of a punch forcing the metal into a die cavity. Deep drawing products in modern industries usually have a complicated shape, so these have to undergo several successive operations to obtain a final desired shape. Trimming of the flange is one of those operations and that is used to remove the ears i.e. to have uniform shape of the flange on all the sides of the final product. These ears are often wavy projections or unevenness formed along the edge of the flange or end of the wall of the cup as shown in Fig. 1. These are formed due to uneven metal flow in different directions, which is primarily due to the presence of the planar anisotropy in the sheet.

The thesis follows the style and format of *ASME Journal of Engineering Materials and Technology*.

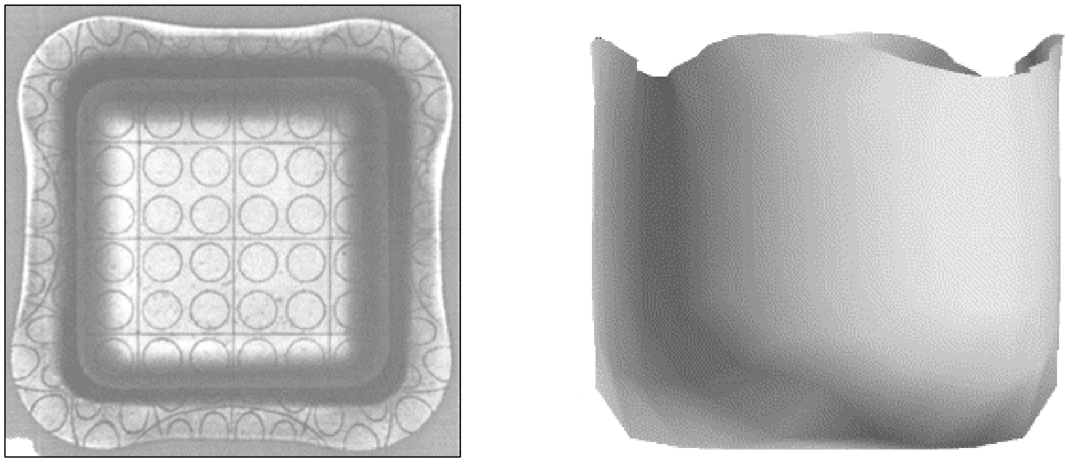


Fig. 1 Diagram showing earing at the flange and end of the wall
(Source: [1] and [27])

Earing is highly undesirable not only because it adds on an additional processing step but also because of the metal representing ear will undergo deformation and that demands extra load and work. However forming without trimming is difficult but not impossible since even a small variation in process parameters can result in large deviation from the desired shape and performance of the product. One of the ways to get rid of trimming or ears formation is to find the optimal blank shape which is referred to an initial blank shape to produce a final cup shape with uniform flange. The optimal blank not only prevents the wastage of material or reduces product development period but also improves product quality and reduces occurrence of defects like wrinkling and tearing to some extent. This optimization process is based on the trial and error method owing to complex nature of the material and inherent characteristics of metal forming process variables like tool shapes, punch lubrication, blank holder force, and punch speed. An experimental trial and error method to determine the best blank shape for making a cup free from all defects is very expensive and time consuming, so numerical simulation tools have been found as an attractive and effective alternative.

1.1 Process description

The typical set up of deep drawing process is shown in Fig. 2

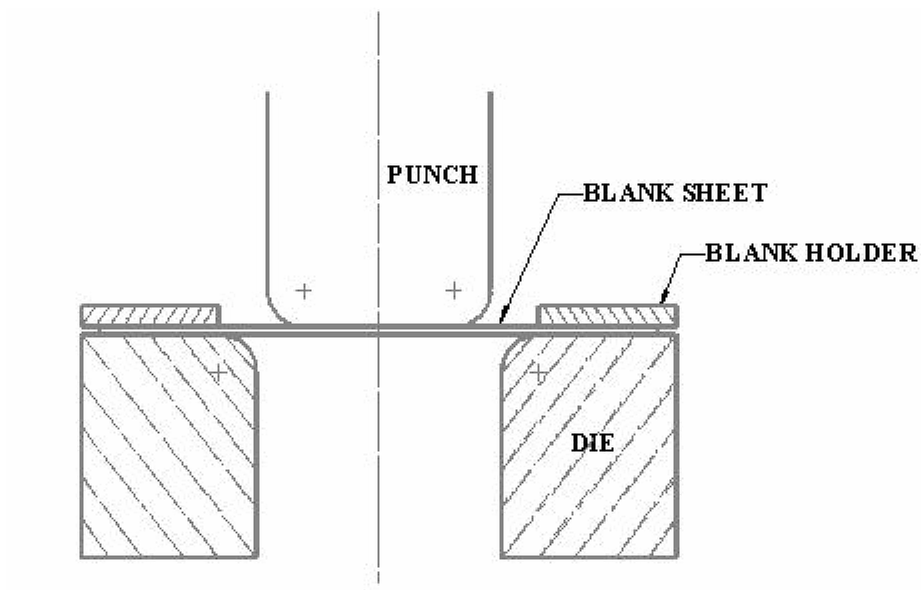


Fig. 2 Experimental set up of deep drawing process

The typical deep drawing process is described as follows:

- The sheet metal blank is held between the die and the blank holder.
- The blank holder is loaded by uniform or varying pressure/force to prevent wrinkling and to control the flow of sheet metal.

- The punch is pushed into the die cavity, simultaneously transferring the specific shape of the punch and the die to the sheet metal blank, thus forming a cup.

1.2 Research objective

The main objective of the proposed research is to find the optimal blank shape that is to be used in the deep drawing process to produce a cup of required shape and size. For general deep drawing operations, most people define the optimal blank shape as that blank profile which can be deformed into a cup with either a uniform flange profile or uniform rim height i.e. cup free from ears. However it is not easy to find an optimal blank shape because of complexity of deformation behavior and there are couple of process parameters like die radius, punch radius, punch speed, blank holder force and amount of friction which affects the result of the process i.e. tearing, wrinkling, springback and surface conditions such as earing. Even a slight variation in one of these parameters can result in defects. Until now, the optimal blank shape design along with the input of optimal process parameters is performed by a trial and error method based on the expertise of the engineer. But recently, in order to address the change of demand from mass production to batch production for higher quality products in ever shorter time, this experimental trial and error technique has turned out to be very expensive and time consuming. Therefore, numerical simulations of sheet metal forming processes based on the finite element method (FEM) represent a powerful tool for prediction of forming processes.

1.3 Literature survey

Since the optimal blank design is an attractive subject to the sheet metal engineers, many investigations have been carried out to obtain the optimal blank shape that could be deformed into the net shape. Several methods have been developed and lots of different approaches have been tried.

Chung and Richmond [2, 3] proposed a direct design method and its theoretical basis, which is called ideal forming theory to get an initial blank shape. But real forming conditions such as blank holder forces, friction forces, tool geometry, etc. are not considered so the calculated blank shape had some shape errors. No effort was also made to simulate the earing. Park et al. [4] suggested a method that requires FE analysis to get an optimum blank shape. In this method, the ideal forming theory is used in combination with a deformation path iteration method. But ideal forming theory requires material elements to deform along the minimum plastic work paths, assuming that such paths provide optimum formability [2, 3]. Chung et al. [5] developed a sequential design procedure to optimize sheet-forming processes based on ideal forming theory, FEM analysis and experimental trials. They used this procedure to design a blank shape for a highly anisotropic aluminum alloy sheet that resulted in a deep draw circular cup with minimum earing.

Toshiko et al. [6], Gloeckl and Lange [7], Duncan and Sowerby [8], Chen and Sowerby [9] have used the slip line field method to obtain an optimum blank shape. The slip line field theory assumes plain strain conditions and material is considered rigidly perfectly plastic Mises solid.

Liu and Sowerby [10] proposed a method based on potential flow to establish the optimum blank shape for prismatic cup drawing. Lo and Lee [11] tried to improve upon this potential flow method by introducing the effects of friction and material anisotropy. However, in this potential flow approach, the material hardening effects are not considered.

Sowerby et al. [12], Blount et al. [13], Gerdeen and Chen [14] have used a geometric mapping method to determine the blank shape. In geometric mapping, the final geometry of a sheet metal part that is to be drawn is mapped point by point back to a flat blank.

Kim and Kobayashi [15] have proposed a geometrical scheme to determine the contour shape of the blank for rectangular cup drawing. They achieved this by calculating the flow lines of the material points in the blank during drawing [16]. Chung and Shah [17] used finite element simulation in conjunction with the six-component Barlat yield criterion to simulate earing formation. The main focus of the study was to verify the performance of planar anisotropy of the Barlat’s criterion. Barlat et al. [18] suggested an inverse design approach in conjunction with a mathematical technique to get an optimum blank. They took into consideration the actions of the tools in contact with the blank sheet and planar anisotropy of the material. Hu et al. [19] explained the effect of varying planar anisotropy on ear patterns. They proposed a method of controlling the magnitude of earing though no attempt was made to optimize the shape of the blank required to produce a product of desired shape and performance.

Gea and Ramamurthy [16] have proposed a numerical scheme to maximize the drawability and to determine the optimal starting blank design for square cupping operations. Fracture failure and draw-in failure have been studied to maximize the drawability. Ohata et al. [20] proposed a method called the “sweeping simplex method” used in conjunction with a FEM code to find the optimum condition of the sheet metal forming processes which includes lubrication, blank shape, die and punch shapes, forming schedule and material. Iseki and Murota [21] have proposed a numerical modeling of non-circular cup drawing processes to determine the shape of the blank that can be formed be into a cup of uniform height. For this purpose, they first analyze the deformation of the flange region of the cup using FEA. The outcome of this analysis is then used to determine the optimal blank geometry assuming the sheet metal as isotropic [16]. Mamalis et al. [22-24] used the finite element techniques to study the effect of material and forming characteristics in sheet metal forming processes. Examples of square cup and cylindrical cup have been investigated. No effort has been to optimize the blank shape. Shim et al. [25-27] have used sensitivity analysis methods along with FEM code to get the optimum blank shape design. These methods need a couple of deformation analysis at each design step to reach to the optimum blank shape. Son and Shim [28] proposed a new method called initial nodal velocity (INOV) of boundary nodes, to obtain an optimal blank shape. In this method, the ratio of initial velocity to the whole path length during deformation is utilized.

Among other notable methods used to get the optimum blank shape are: inverse method [29, 30], backward tracing [31], volume addition/subtraction method [32], analogy method [33, 34] and iteration method in conjunction with some technique using FE code [1, 35-37].

1.4 Research approach

The benefits offered by optimization of blank that is to be used in drawing the uniform flanged cup of required shape and size will be characterized based upon its effect on successful achievement of desired product and reduction of cost and time. The present work has been divided into the following categories:

- FE model is construted representing physical process from a macroscopic point of view. A target contour of the flange having a uniform trimming allowance is defined. The process of optimization of blank has been divided into a certain number of stages and each stage has its own target contour. This helps in improving the computational efficiency i.e. less CPU time to reach to an optimal blank design.
- Explicit non-linear finite element code LSDYNA is used to simulate the deep drawing process.
- Shape error function is defined that is used to measure the deviation of the deformed contour from the target contour quantitatively.
- The material of the sheet is considered to be anisotropic. The direction of flow of material is observed at various steps and accordingly the blank shape is modified.

CHAPTER II

METHODOLOGY

2.1 Overview

The proposed systematic approach of obtaining an optimal blank shape to achieve the final required product has been outlined completely in the Fig. 3.

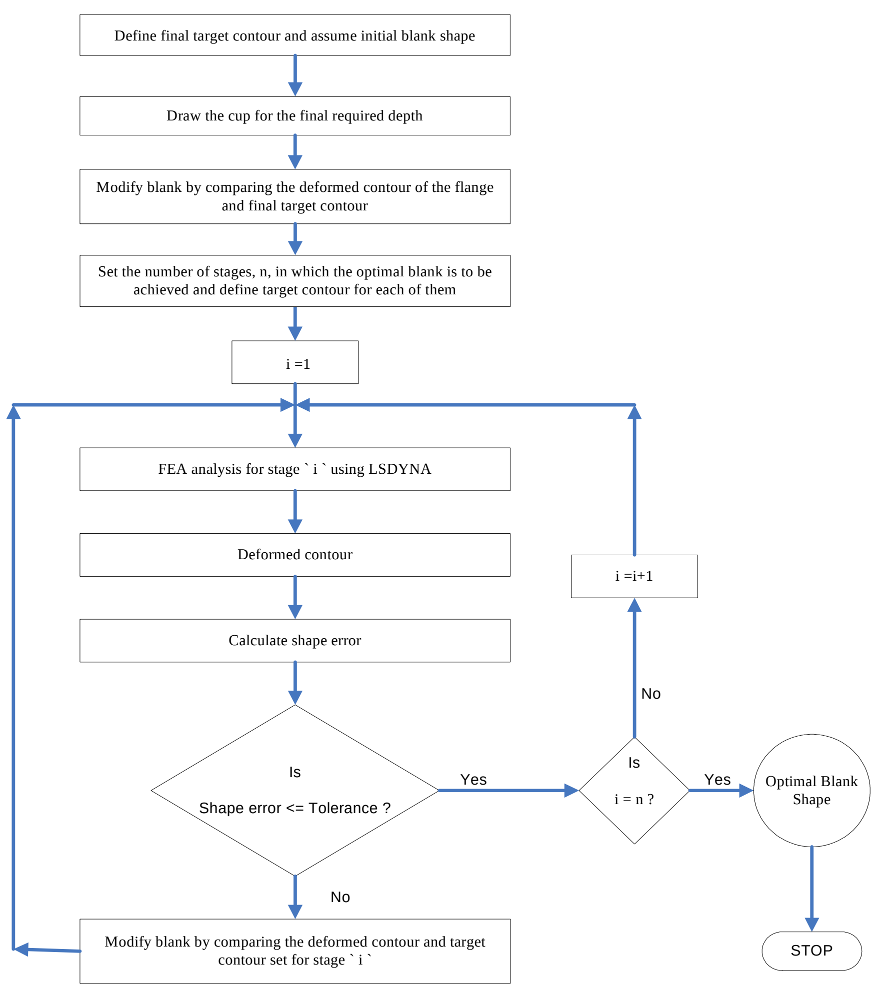
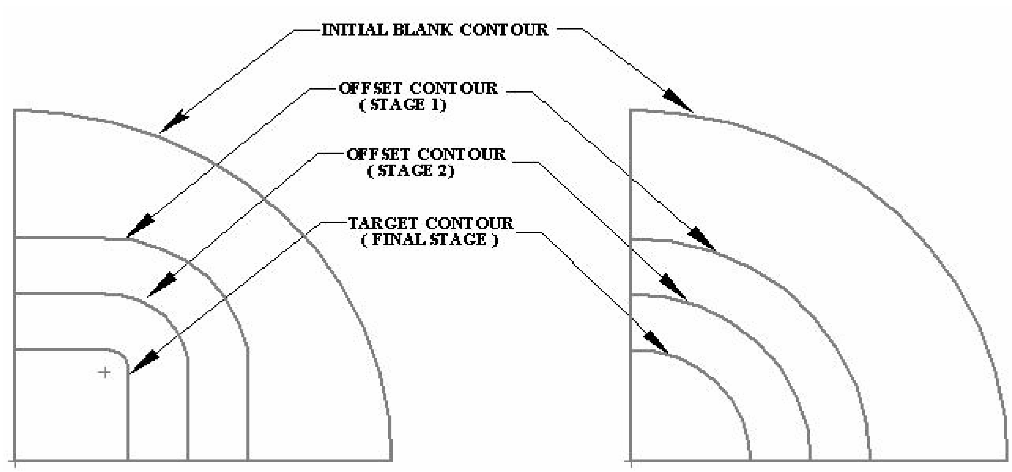


Fig. 3 Flow chart of methodology

Our aim in this study is to have an optimal blank shape that upon deep drawing process produces a cup of required depth having a uniform trimming allowance at the flange. Finite element analysis software LSDYNA is used to simulate the process. This process of obtaining an optimal blank shape has been split up into multiple numbers of stages as shown in Fig. 4. Every stage has got its own target contour, which is basically the offset contour to the final target contour of the flange of the required cup. These stages lie in between the initial blank contour and the final target contour. The final target contour is considered as the final stage of the process.



Square cup **Cylindrical cup**

Fig. 4 Various stages set for FE analysis

There are basically two advantages of dividing the optimization process into stages. First, if there would be any defect in the chosen parameters for finite element simulation, that can be known in the first stage itself since it is reached to the final target contour gradually after confirming all the target contours of earlier stages. This helps us in saving a lot of time in case of any defect. Second, since the blank is modified to have some specific desired shape at the flange in each stage, so after confirming the target contour of first stage when we go to second stage, the deformed contour of the flange shows comparatively less deviation from the second stage target contour as compared to if we directly comes to second stage from the initial contour. This deviation can be rectified in a shorter time. Similar is the case for other stages. So splitting up the process into multiple numbers of stages helps in achieving the optimal blank shape faster. There is no fixed criterion to decide upon the number of stages required for obtaining an optimal blank shape. Usually the first stage is set at around the mid of initial contour and the final target contour and rest are at equal distances from each other. At the end of each stage, a different blank shape will be achieved which will further act as the starting blank for the next stage.

To start with the process of obtaining an optimal blank shape, we need an initial blank that will undergo FE analysis to study deformation process. Circular shaped blank is considered as the best option to start with [16]. The diameter of the circular blank is found by line analysis technique. For non-axisymmetrical cups, this technique is applied both along the length and breadth and the one that gives a greater value will be considered for the diameter.

The size of the blank obtained by the line analysis technique will generally be significantly bigger than the optimal blank, since the effect of stretching and thickening has not been taken into account. So to make the blank size approximately closer to the optimal blank size, the circular blank is first simulated to the final required depth and then modified by comparing the deformed contour of the flange and the final target contour. This is considered as the zeroth stage of the process. The modified blank obtained is now further used for the first stage.

In our approach, at the end of every stage we have to have our deformed contour of the flange obtained by doing the FE analysis lie on the target contour set for that particular stage. In each stage, for each iteration, FEA is terminated when one of the edge nodes reaches the target contour. Since it is very difficult to make the deformed contour coincide with the target contour, the concept of shape error is introduced. It tells us about the quantitative geometric deviation of the deformed contour from the target contour. Its value is usually fixed based on some percentage of the final depth of the cup. In the present study, the shape error allowance value has been fixed to be 0.25mm. At the end of each iteration or deformation analysis, the value of shape error is calculated. The blank is modified and the deformation process is analyzed again until the calculated value of shape error reaches a preset specified allowance. The process is repeated for all the stages except the final one.

2.2 Determination of initial blank geometry

To start with the process of obtaining an optimal blank shape, we need an initial blank that will undergo FE analysis to study deformation process. A new method called line analysis technique has been proposed to determine the initial blank geometry.

This technique is employed to decide upon the diameter of the circular blank used in the very first step in the process of obtaining an optimal blank shape. An ideal case is considered in this technique that the whole blank material is drawn into the cup shape without any thickening and stretching effects. The diameter of the blank, $D_{b,}$ is calculated by measuring the length of the line, starting from any point on the edge of the flange of the final required cup (as in Fig. 5) and goes straight to the exactly opposite point on the other side of the flange along the drawn cup, passing through the centre lying on the base of the cup.

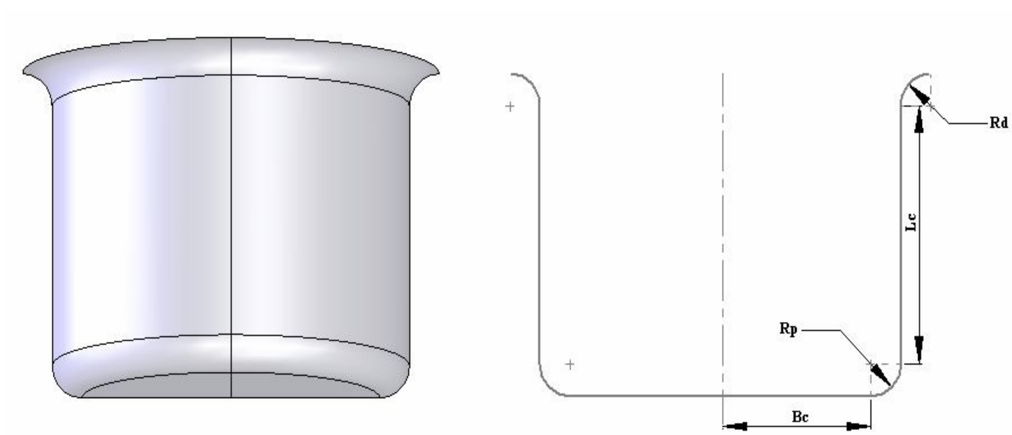


Fig. 5 Diagram showing line analysis technique

The diameter of the blank, $D_{b,}$ is calculated using the following relation:

$$D_b = 2\left(\frac{2\pi R_d}{4} + L_c + \frac{2\pi R_p}{4} + B_c\right) \tag{2.1}$$

Where

R_d = Die profile radius

R_p = Punch radius

L_c = Height of flat portion of cup

B_c = Width of flat portion of cup

There is one more method, called the graphical method, to determine the shape of initial blank geometry (see appendix C).This method is considered more suitable to draw rectangular cups. For more complex shapes, geometric mapping or slip line field methods can be applied to obtain the initial blank shape.

2.3 Shape error

Shape error, $\boldsymbol{\mu_{error}}$, is defined as the absolute mean of the shape difference between the deformed contour of the flange and target contour. It is calculated by taking the mean of the absolute values of the distances between the nodal points of the deformed contour of the flange and the corresponding nodal points supposed to be on the target contour.

$$\mu_{error} = \frac{1}{n}\sum_{i=1}^{n}\left| \; d_i \; \right| \tag{2.2}$$

Where

d_i = distance between the nodal point of the deformed contour of the flange and the target contour along the direction of material flow in the last deformation step shown in Fig.6.

n = total number of nodes located on the boundary of the blank.

2.4 Modification of blank

The basic idea used in the modification of a blank is that the material is added to or subtracted from the current blank wherever it has been found less or more, respectively, by comparing the deformed contour of the flange and the target contour.

Fig. 6 shows the material flow direction of a node on the boundary of the blank. Since metal forming is a non-linear deformation process, so the node will move along a non-linear deformation path during deformation. Consequently the material direction will be changed time to time during deformation and therefore final direction will be different from initial direction of the material flow. A small variation of the initial position results in a different final position. The fact that the desired shape after forming is achieved means that every node on the boundary is on the target contour after deformation. In order to make the nodes lie on the target contour, the initial position of the node should be repositioned considering the amount of shape error and material flow direction [28].

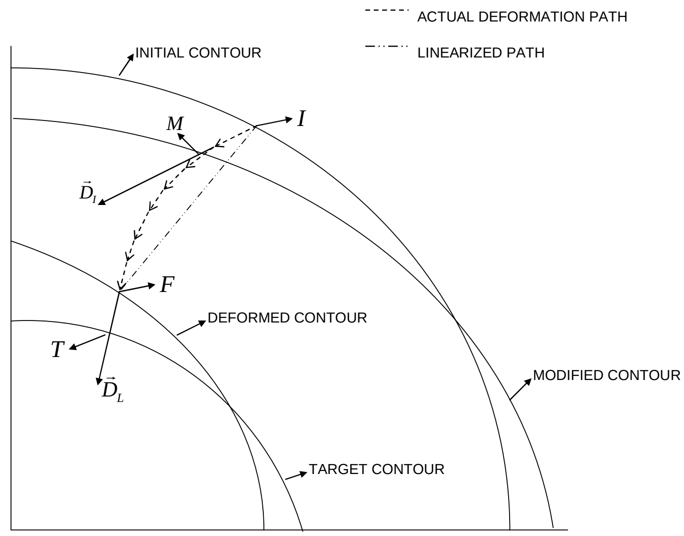


Fig. 6 Diagram showing movement of a node on the boundary

In order to reposition the nodes located on the boundary of the previous blank before a new iteration, we will measure the distance between a nodal point of the deformed contour, $\vec{F}_i$, and the corresponding nodal point supposed to be on the target contour, $\vec{T}_i$. The target contour is set in the plane of the blank sheet before deformation and all the nodes defining the outermost boundary of the blank are assumed to remain in the same plane as that of the target contour throughout the deformation. The supposed position of a node on the target contour is found by taking the intersection of the line of material flow of the node in the last deformation step of an iteration and the target contour. Then the position of the node on the current blank before deformation is moved by the same distance, as obtained by comparing the deformed contour and target contour, along the line of material flow of that particular node in the first deformation step of an iteration.

Let $\vec{I}_i$ represent the position vector of an i^{th} nodal point located at the boundary of an initial blank before deformation and $\vec{F}_i$ represent a position vector of the node after final deformation. With the initial blank defined by a group of boundary nodes I , the deformation process is analyzed by finite element method. Unless F is on the target contour T , the position of the corresponding nodal point before deformation $\vec{I}_i$ should be repositioned repeatedly.

$$\vec{d}_i = \vec{\mathrm{T}}_{\mathrm{i}} - \vec{F}_i \tag{2.3}$$

$$\vec{M}_{\mathrm{i}} = \vec{I}_i \pm \left|\vec{d}_i\right| \vec{D}_{Ii} \tag{2.4}$$

Where

$\vec{M}_{\mathrm{i}}$ = position vector of i^{th} nodal point on the modified contour.

$\vec{\mathrm{T}}_{\mathrm{i}}$ = position vector of i^{th} nodal point on the target contour.

$\vec{D}_{Ii}$ = unit vector of i^{th} nodal point in the direction of first deformation step of an iteration.

$\vec{D}_{Li}$ = unit vector of i^{th} nodal point in the direction of last deformation step of an iteration.

Positive sign is used in the equation 2.4 if the material is to be subtracted and the negative sign is used if the material is to be added.

When we start the analysis for the final stage we will find that the material of the blank obtained from the previous stage is not sufficient enough to draw the cup for the required depth. This is because of the fact that as the drawing operation progresses, the material in the flange area moves inward towards the die cavity and gets compressed in the circumferential direction and thereby material becomes thicker than the blank. In the zeroth stage, since the blank is drawn for the final required depth so after modification the blank used in the first stage had gotten nearly the same amount of volume of the material as is required to have the optimal blank size. During modification of the blank in the subsequent iterations, the volume has not been considered as a result of which a significant amount of volume of material is lost which would ultimately causes for lesser depth than the required. In order to compensate for this loss of material, material is added to the blank to be used for the final stage. The amount of material to be added is found as follows:

Simulate the blank to the final target contour without considering the depth. Measure the depth of the cup that has been achieved, say *h*. Let X be the distance between the outermost node on the boundary of the blank lying on the x-axis before deformation and the corresponding node after deformation (as shown in Fig. 7). If D is the final depth that has to be achieved, a temporary offset contour at a distance C from the final target contour is set just for the purpose of adding the material.

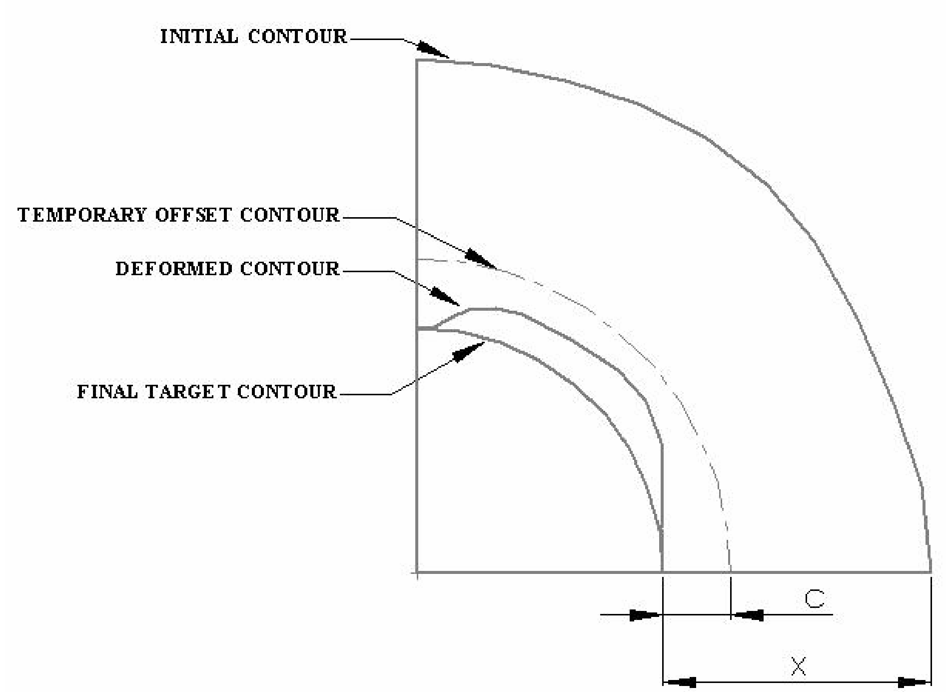


Fig. 7 Position of temporary offset contour

The value of C is calculated by using the following relation:

$$C = \frac{X\,(D - h)}{h} \tag{2.5}$$

This temporary offset contour is compared with the deformed contour and the blank is modified which will be further used for the final stage.

CHAPTER III

NUMERICAL SIMULATION RESULTS

3.1 Introduction to simulation

In order to verify the proposed approach of obtaining an optimal blank shape to achieve the final product in the deep drawing process, examples of square cup and cylindrical cup have been considered. The FEM software LSDYNA is used to simulate and analyze the deformation processes. LSDYNA is explicit nonlinear finite element software used extensively to simulate the different type of metal forming processes like deep drawing, stretch forming, bending, etc.

In the present study, the model is constructed using the 3D CAD software *SolidWorks* and then converted into a finite element mesh using the preprocessor *Altair HyperMesh*. The same model is used in all the iterations with different blank shapes. Due to shape symmetry and to save CPU time, only a quarter part of the actual geometry is modeled and simulated.

To get accurate results, the selection of an appropriate material model is considered as the most important part of the simulation. The selected material model should have the capability to take care of the deformation process considering each and every material property as per the requirement. In the present study, the anisotropic plastic material model “MAT_ANISOTROPIC_PLASTIC” is used and it requires the input of various material properties such as mass density, young’s modulus of elasticity, poisson's ratio, initial yield stress, R_0, R_{45} and R_{90}. The material, mild steel, is used for the analysis. The detailed material properties are given in Table. 1.

Table 1
Material properties of blank sheet

Property	*Value*
Sheet material	Mild steel
Young's modulus(GPa)	210
Mass density(gm/cc)	7.80
Poisson's ratio	0.30
Initial yield stress(MPa)	286
R_{00}	2.15
R_{45}	1.78
R_{90}	2.43
Coulomb coefficient of friction	0.10
Stress strain relation(MPa)	$\sigma = 565.32(0.007177 + \varepsilon_p)^{0.2589}$

The blank is simulated using four node Belytschko-Tsay elements employing five through-thickness integration points whilst the punch, the die and the blank holder are simulated as rigid bodies just on a purpose of saving CPU time cost. All nodes of the punch and the blank holder are constrained in all the directions except along the punch motion whereas for the die these are completely constrained. The material characteristics of the punch, the die and the blank holder are the same. The contact between the blank and the tools is a standard master and slave contact interface defined using the "CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE" option as implemented in LSDYNA. The frictional conditions at the blank/blank holder interface, the blank/punch interface and the blank/die interface are considered to be the same. Both the static and the dynamic friction coefficients between all contact surfaces are set at 0.10. The punch is made to move into the die with a constant velocity. The force on the blank holder is kept constant. To verify the predictive capability of the model, the wall thickness profile of a simulated cylindrical cup along the height of the cup is observed. The cup is drawn for 35mm of depth and initial thickness of the blank sheet is taken as 0.84mm. The result of thickness distribution along the wall is shown in Fig. 8. The thickness distribution is plotted against the height of the cup in Fig. 9. The profile of the curve obtained is the typical nature of, thickness distribution versus height of cup, curve for a deep drawing process. So this curve validates the effectiveness of the model. Two examples have been considered to investigate the effectiveness of the proposed approach.

1. Square cup
2. Cylindrical cup

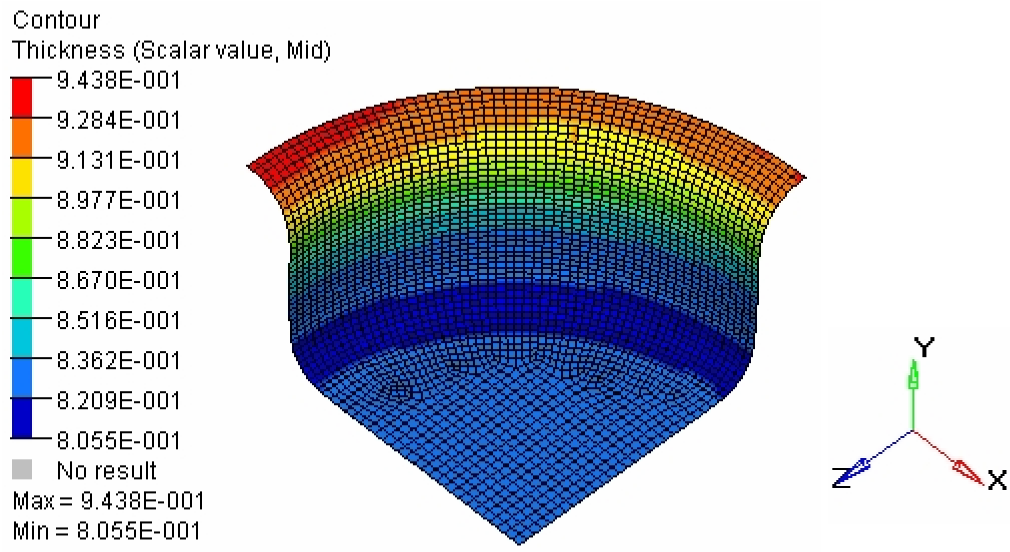


Fig. 8 Thickness distribution along the wall for a cylindrical cup

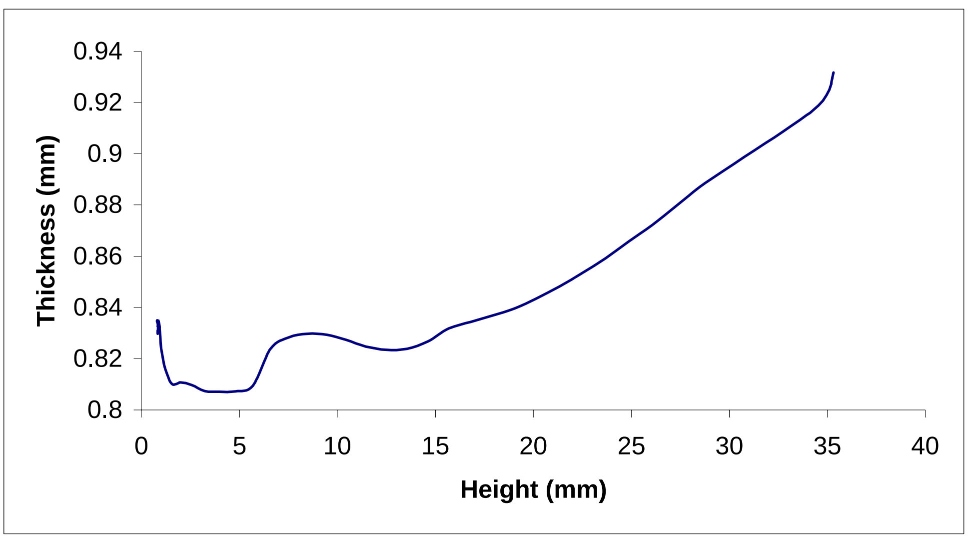


Fig. 9 Thickness profile along the wall at different heights for a cylindrical cup

3.2 Square cup

Finite element model and schematic diagram of the deep drawing process for a square cup is shown in Fig. 10 and Fig. 11, respectively.

The tool dimensions and the process parameters used in the simulation of deep drawing process of a square cup have been shown in Table 2. The exploded view of the finite element mesh is shown in Fig. 12.

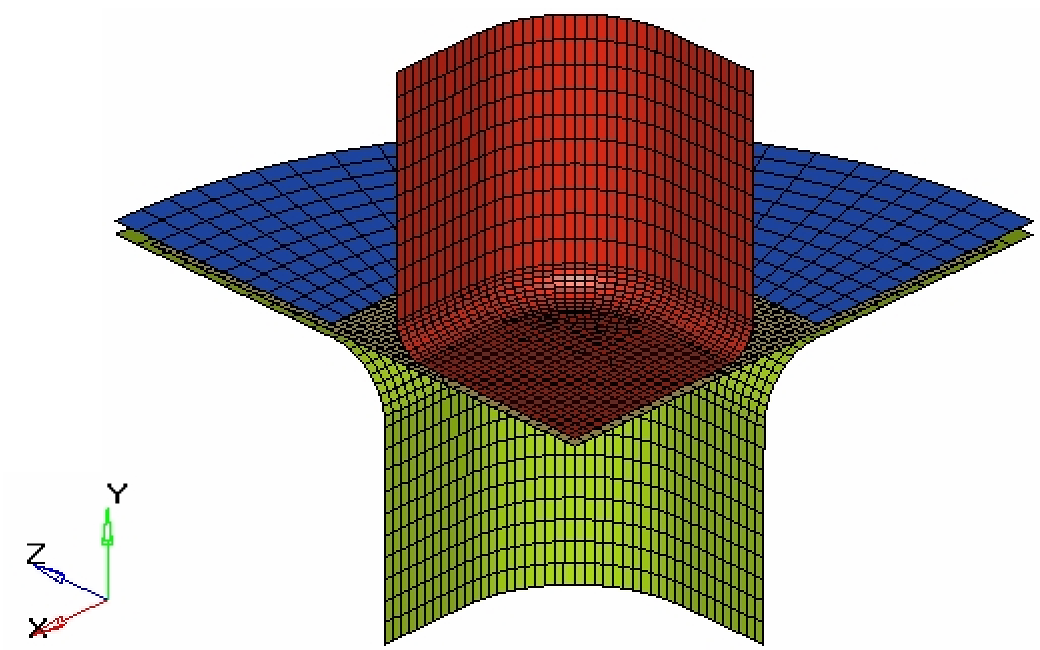


Fig. 10 FE mesh for simulation of deep drawing process of square cup

Deformation analysis is done to obtain the optimal blank shape by taking the process in one stage as well as by dividing it into multiple stages. In case of multiple stage analysis, it has been decided to do it in three stages. The position of these stages has been shown in Fig. 13. The third stage is the final one with the target contour having a uniform trimming allowance of 0.75mm at the flange for a depth of 35mm.The shape error allowance is taken as 0.25mm. To start with the process, initial blank has been assumed to be the circular one having a diameter of 130.68mm found by line analysis technique.

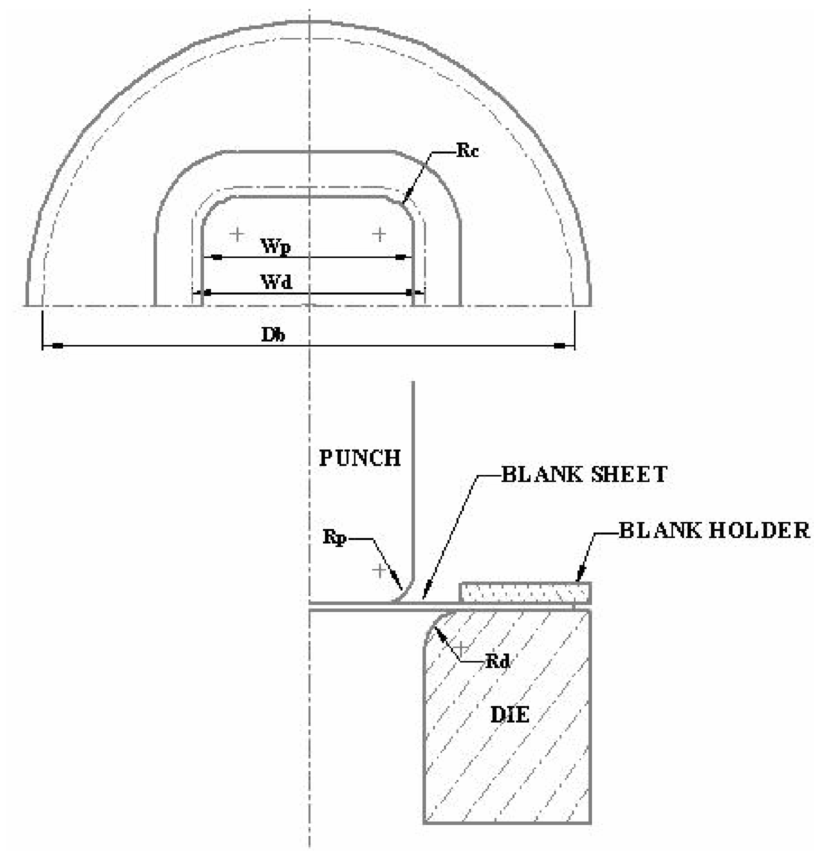
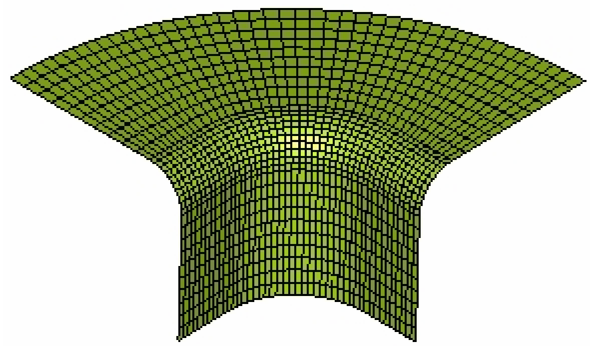
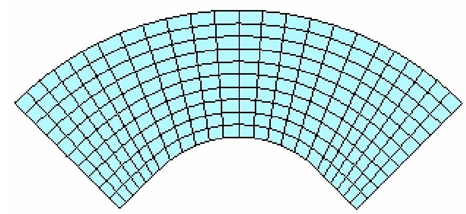
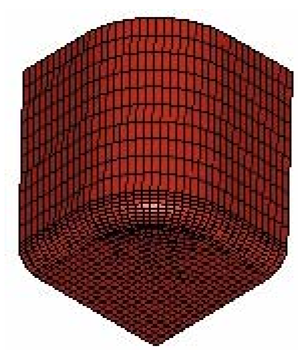


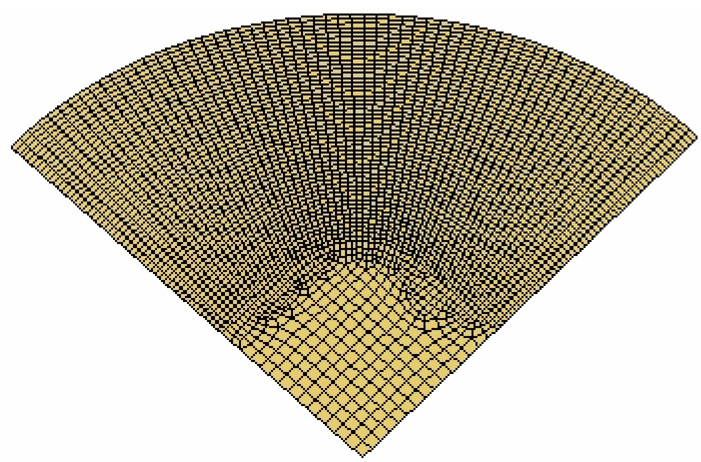
Fig. 11 Schematic diagram of the deep drawing process for a square cup





Die **Blank holder**





Punch **Blank**

Fig. 12 Exploded view of FE mesh for deep drawing process of square cup

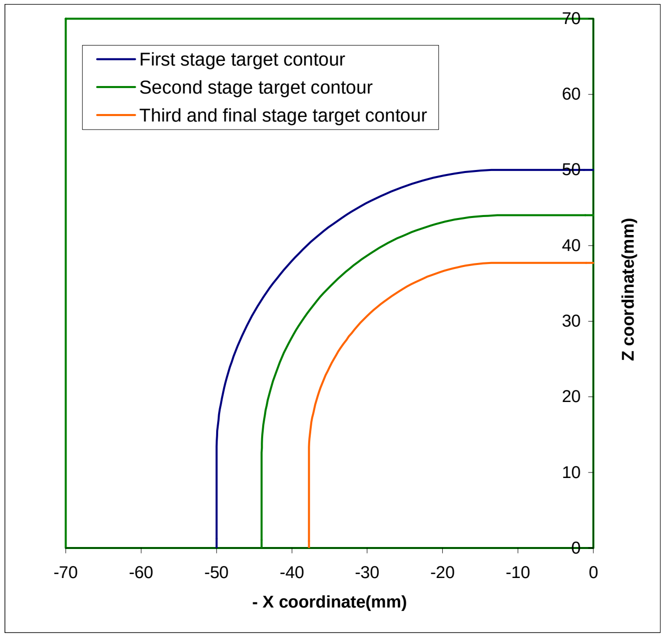


Fig. 13 Diagram showing position of stages for a square cup

Table 2
Tool dimensions and the process parameters used in the simulation of deep drawing process of a square cup.

Parameter	*Value*
Punch velocity(mm/s)	20.0E+03
Blank holder force(KN)	12.0
Shell thickness(mm)	0.84
Width of punch, W_P(mm)	55
Width of die, W_d(mm)	58.5
Punch profile radius, R_p(mm)	4.00
Die profile radius, R_d(mm)	8.00
Punch corner radius, R_c(mm)	15.0
Cup height(mm)	35.0

Fig. 14 shows the progression towards obtaining an optimal blank shape. Fig. 14 (a) shows the analysis for the zeroth stage in which the punch is given the maximum displacement of 35mm, equal to the height of the required cup, just to have the approximate size of the optimal blank. In this stage deformed contour is compared with the final target contour and the shape error is calculated. Shape error has been found to 9.79mm and the blank is modified by using the procedure as explained in section 2.4.

This first modified blank is used to study the deformation analysis for the first stage. Fig. 14 (b)–(c) shows the analysis for the first stage. The first stage target contour is achieved in two deformation analysis or iterations and with one modification of the blank shape. Similarly, the modified blank obtained as a result of first stage is further used for the deformation analysis of the second stage. Fig. 14 (d)-(e) shows the analysis for the second stage. The second stage target contour is also achieved in two iterations and with one modification of the blank shape.

Now before going for the final stage, shown in Fig. 14 (f)-(h), it is to be checked that whether the material of the blank obtained as a result of second stage is sufficient enough to draw the cup of the required depth having a uniform trimming allowance at the flange. Since the volume has not been considered at all while doing the modifications of the blank in the earlier stages, the material has been found to be less. On a purpose of adding the material to make up the required depth, the blank obtained as a result of second stage is deformed up to the final target contour no matter what depth it achieves. Then the temporary offset contour is defined by using the method outlined in 2.4. This temporary offset contour is compared with the deformed contour and the blank is modified. This modified blank is ready to be used for the final stage. The third or final stage target contour is achieved in a total of three iterations and with two modifications of the blank shape.

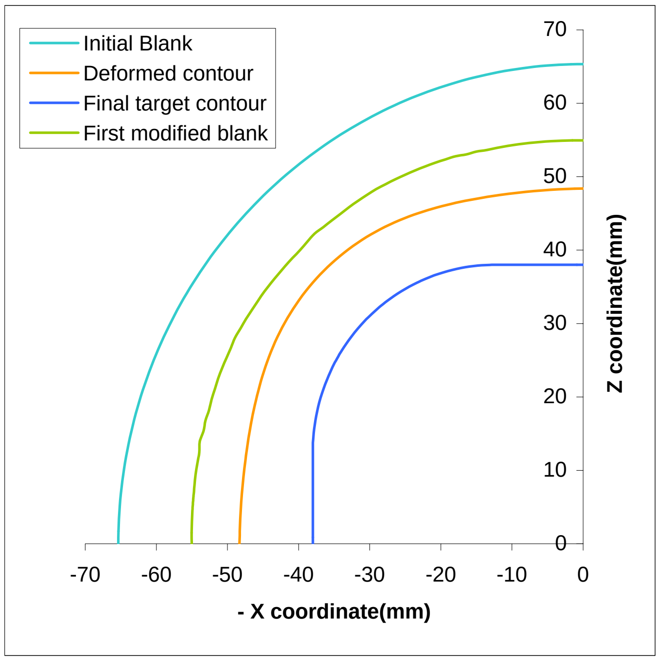


Fig. 14 Progression towards obtaining an optimal blank shape for a square cup using multiple stage analysis
(a) First iteration - Zeroth stage

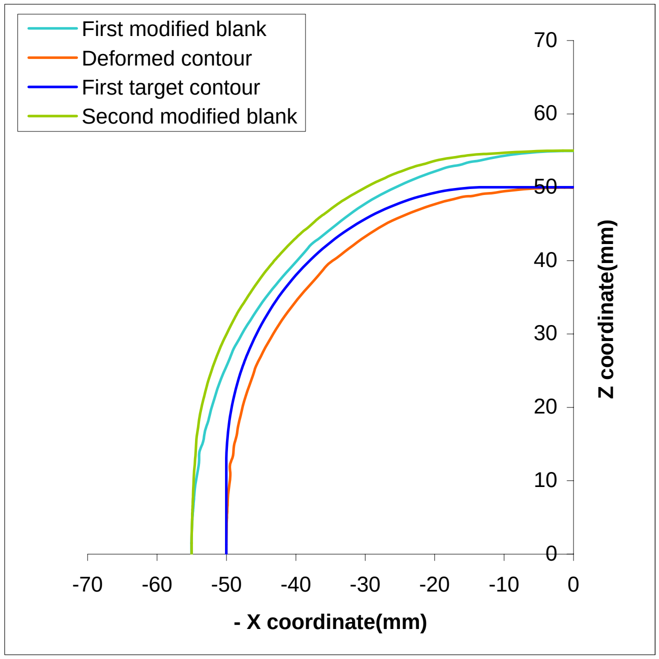


Fig. 14(b) Second iteration – First stage (Run 1)

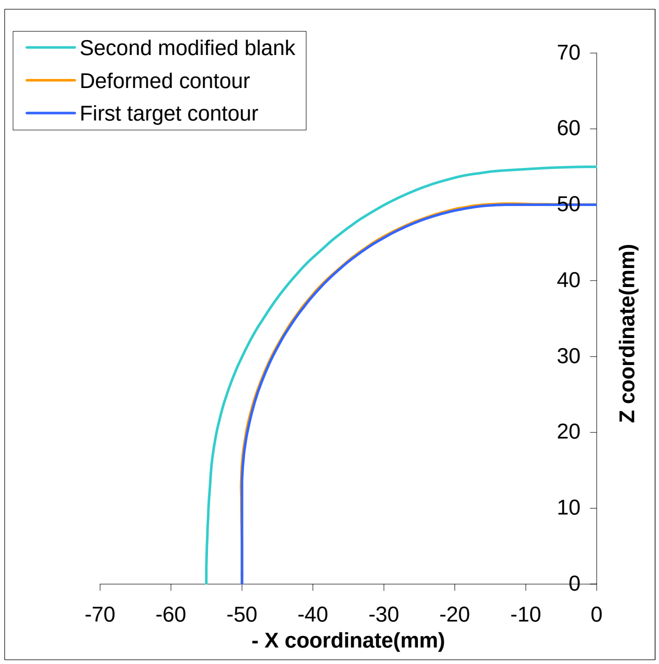


Fig. 14(c) Third iteration – First stage (Run 2)

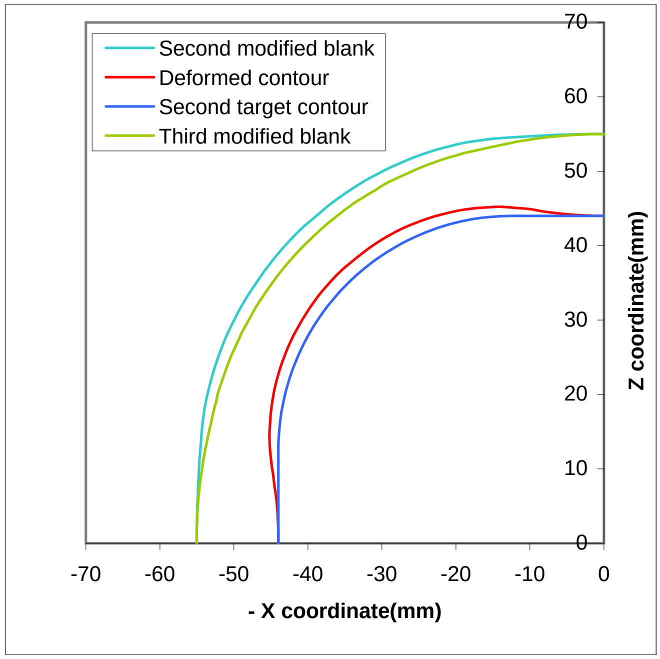


Fig. 14(d) Fourth iteration – Second stage (Run 1)

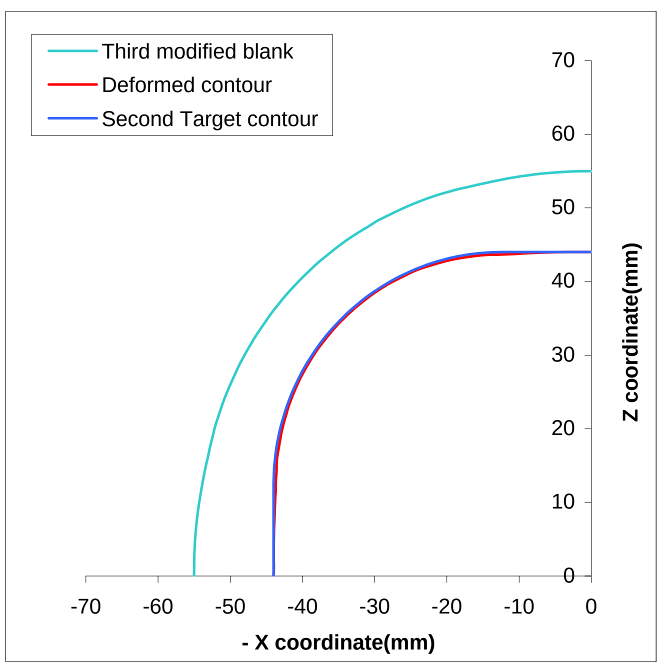


Fig. 14(e) Fifth iteration – Second stage (Run 2)

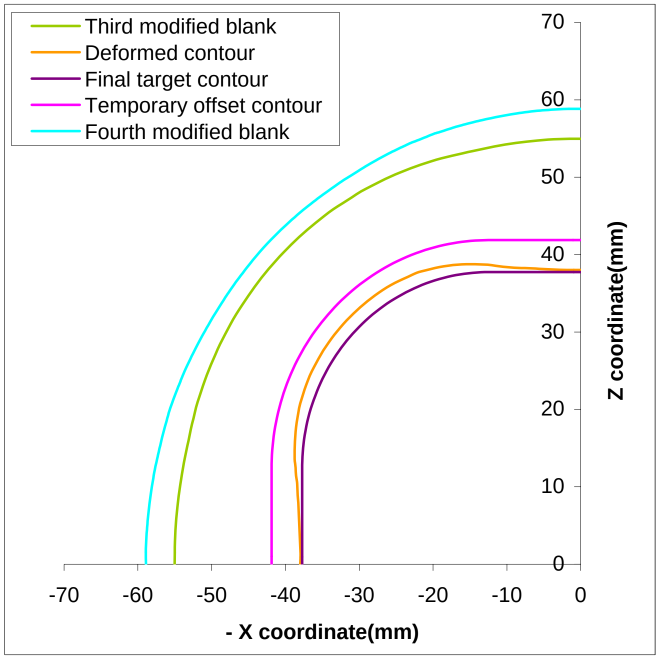


Fig. 14(f) Sixth iteration – Third stage (Run 1)

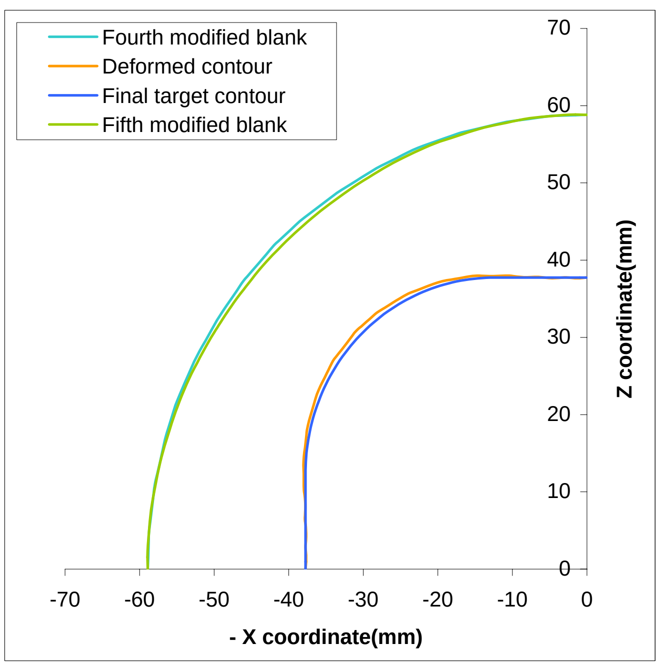


Fig. 14(g) Seventh iteration – Third stage (Run 2)

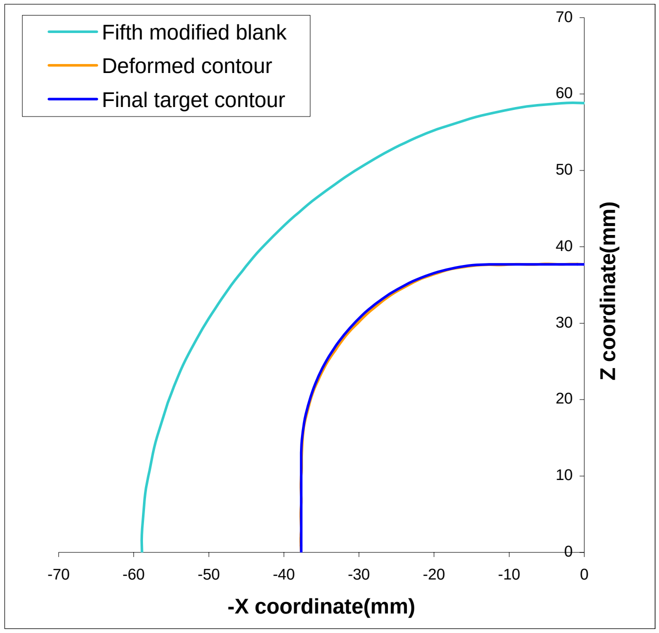


Fig. 14(h) Eighth iteration – Third stage (Run 3)

The fifth modified blank is the optimal blank shown in Fig. 15.

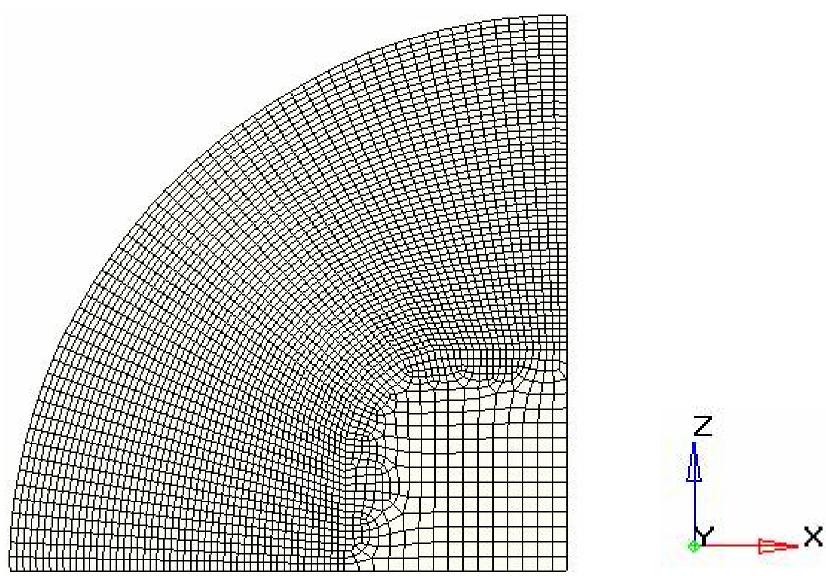


Fig. 15 FE mesh of optimal blank shape for a square cup

The final shape of the flange obtained as a result of the deformation of the optimal blank shape up to a depth of 35mm is shown in Fig. 16.

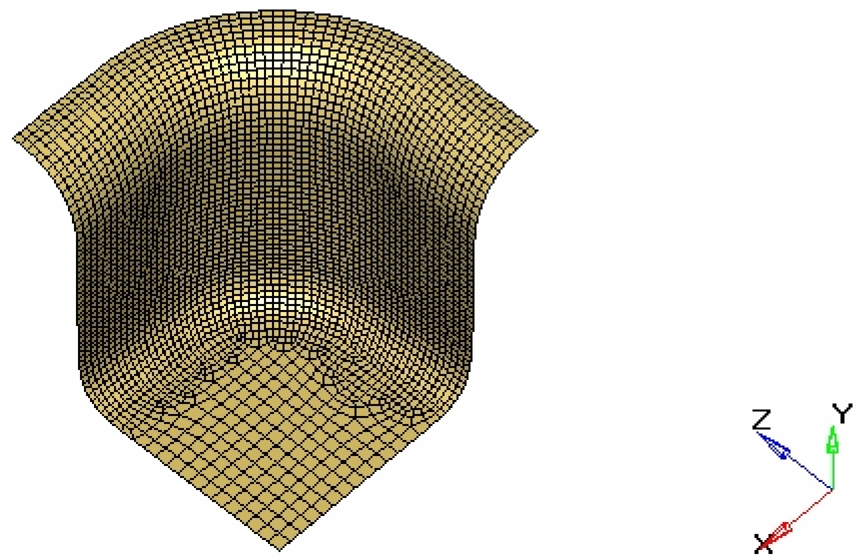


Fig. 16 Deformed shape of the optimal blank of a square cup

The whole process takes a total of eight-deformation analysis or iterations and five modifications to reach to the optimal blank shape. The final shape error has been found to be 0.09mm.The progression of shape error through all the iterations is shown in Fig. 17.

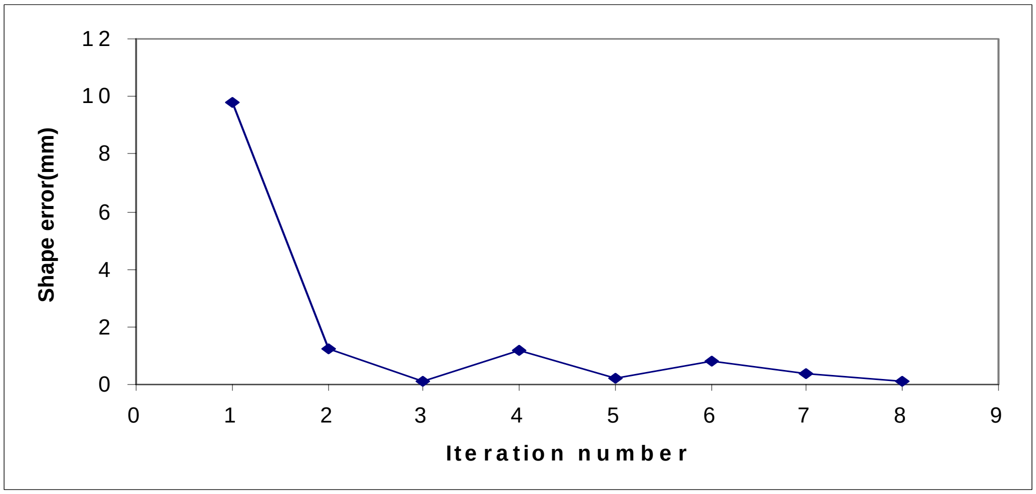


Fig. 17 Shape error history through all the iterations for a square cup using multiple stage analysis

The same process is repeated for the single stage analysis in which there is only one target contour i.e. the final one. In the first three-deformation analysis shown in Fig. 18 (a)-(c), the shape error has been reduced to the value of 0.25mm, which is well within the range of preset value of shape error defined to have the convergence. But at this point the material of the blank is not sufficient enough to draw the cup of the required depth. To make up the depth the temporary offset contour is defined, as shown in Fig. 18 (c), and some material is added to the blank. This modified blank is then subjected to further deformation analysis and it takes three more iterations, shown in Fig. 18 (d)-(f), to obtain the optimal blank shape.

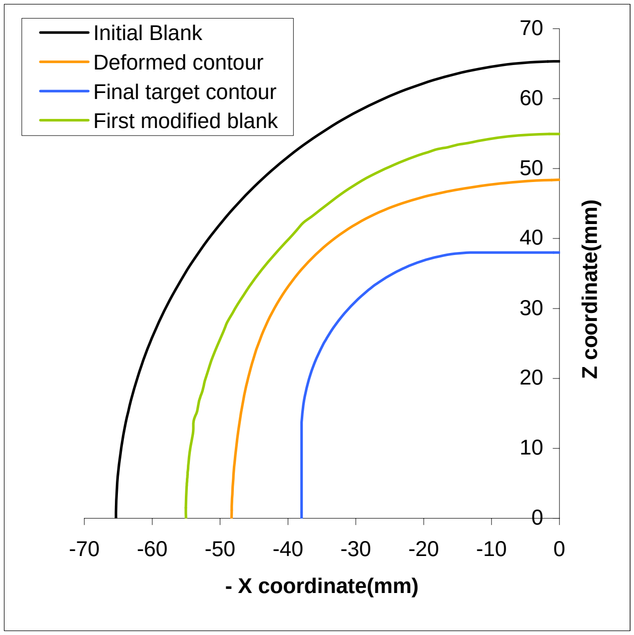


Fig. 18 Progression towards obtaining an optimal blank shape for a square cup using single stage analysis
(a) First iteration

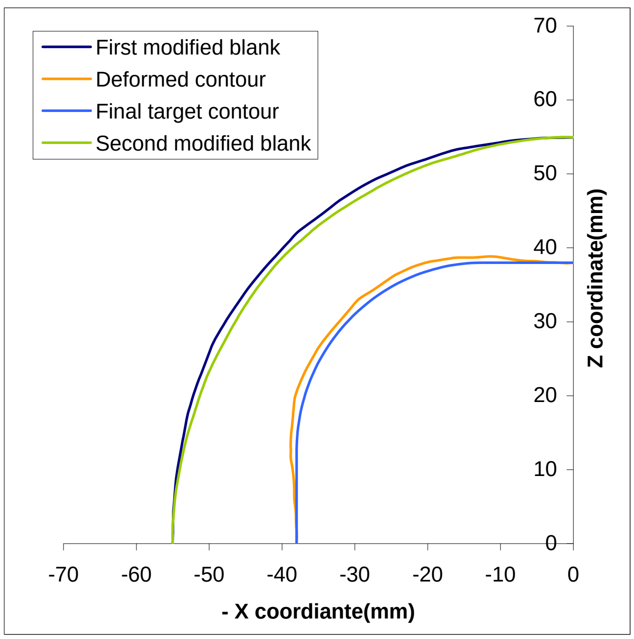


Fig. 18(b) Second iteration

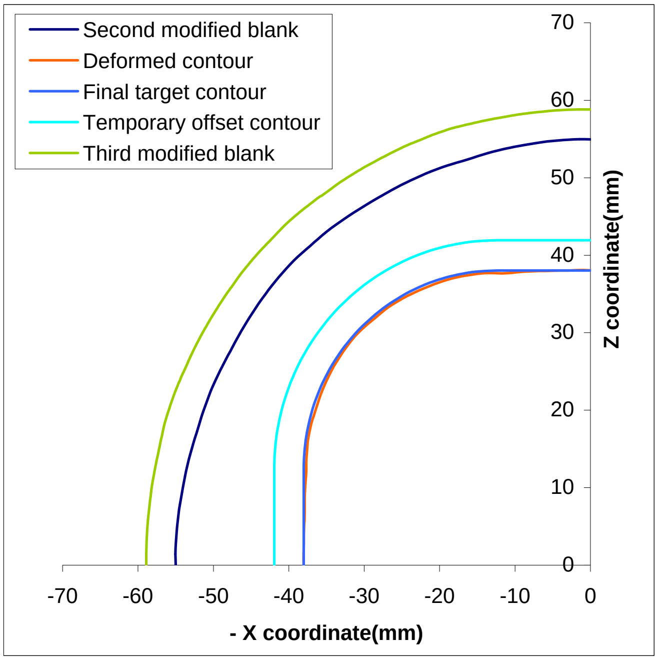


Fig. 18(c) Third iteration

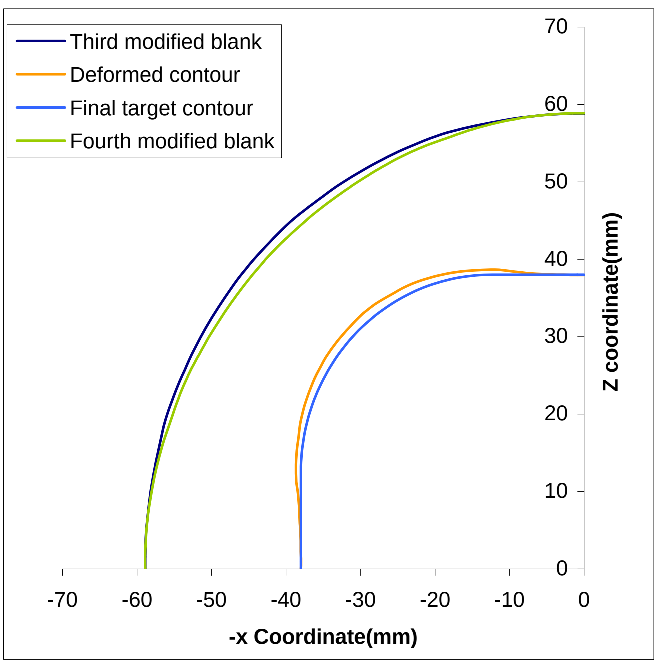


Fig. 18(d) Fourth iteration

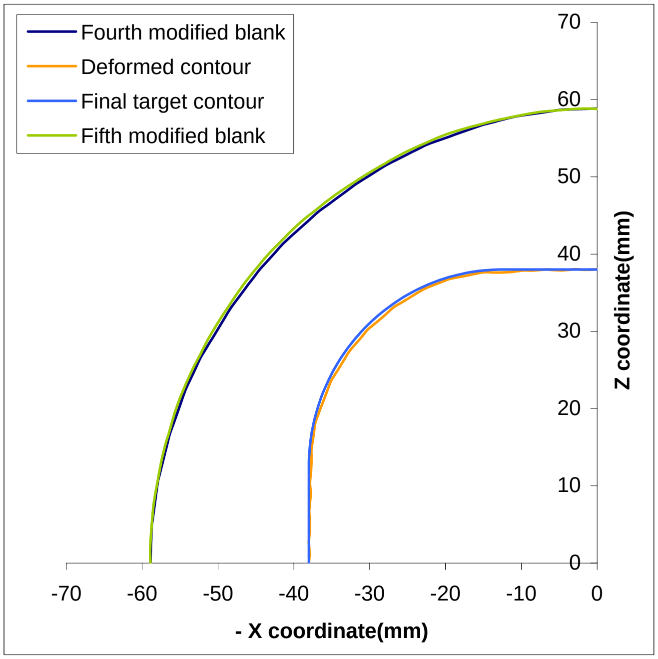


Fig. 18(e) Fifth iteration

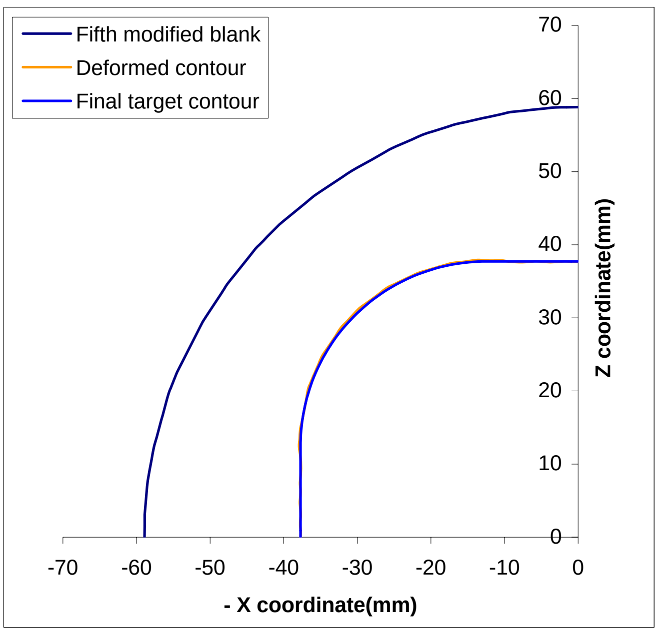


Fig. 18(f) Sixth iteration

So it takes a total of six iterations and five modifications to reach to the optimal blank shape. The final shape error has been found to be 0.11mm. The progression of shape error through all the iterations is shown in Fig. 19.

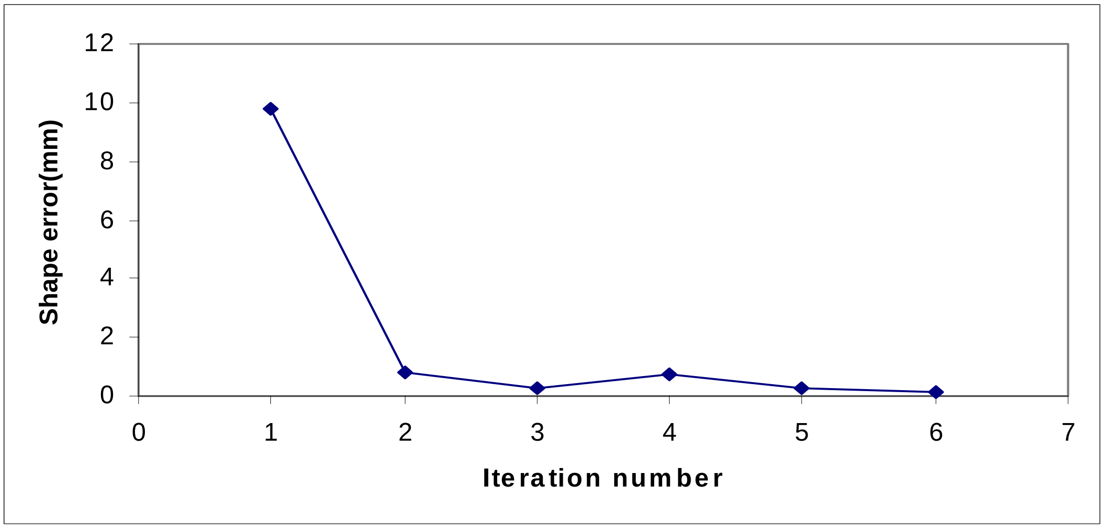


Fig. 19 Shape error history through all the iterations for a square cup using single stage analysis

The results of each iteration for single stage as well as for multi stage analysis in terms of shape error and CPU time cost is summarized in Table 3.

Table 3
Shape error and CPU time history in progression of optimal blank design for square cup undergone single stage and multiple stage analysis.

Iteration No.	For n = 3		For n =1	
	Shape error	CPU time	Shape error	CPU time
1	9.79	24m 34s	9.79	24m 34s
2	1.26	10m 27s	0.83	23m 45s
3	0.12	9m 55s	0.25	23m 23s
4	1.17	16m 15s	0.74	30m 38s
5	0.19	16m 35s	0.30	25m 12s
6	0.83	20m 42s	0.11	24m 40s
7	0.35	25m 10s		
8	0.09	24m 29s		
Total time	150m 7 s		152m 12s	

3.3 Cylindrical cup

Fig. 20 and Fig. 21 shows the finite element model and schematic diagram of the deep drawing process for a cylindrical cup, respectively.

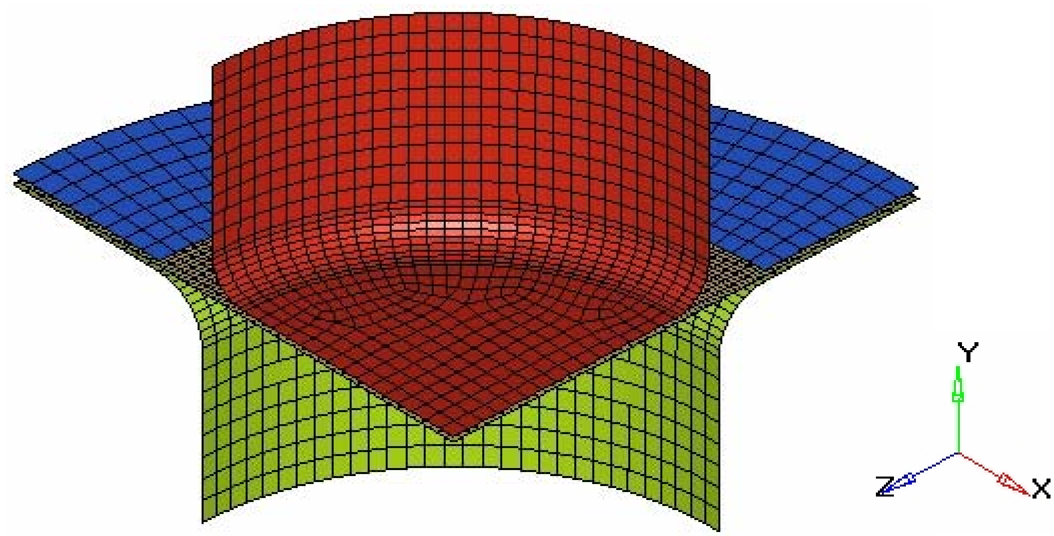


Fig. 20 FE mesh for simulation of deep drawing process of cylindrical cup

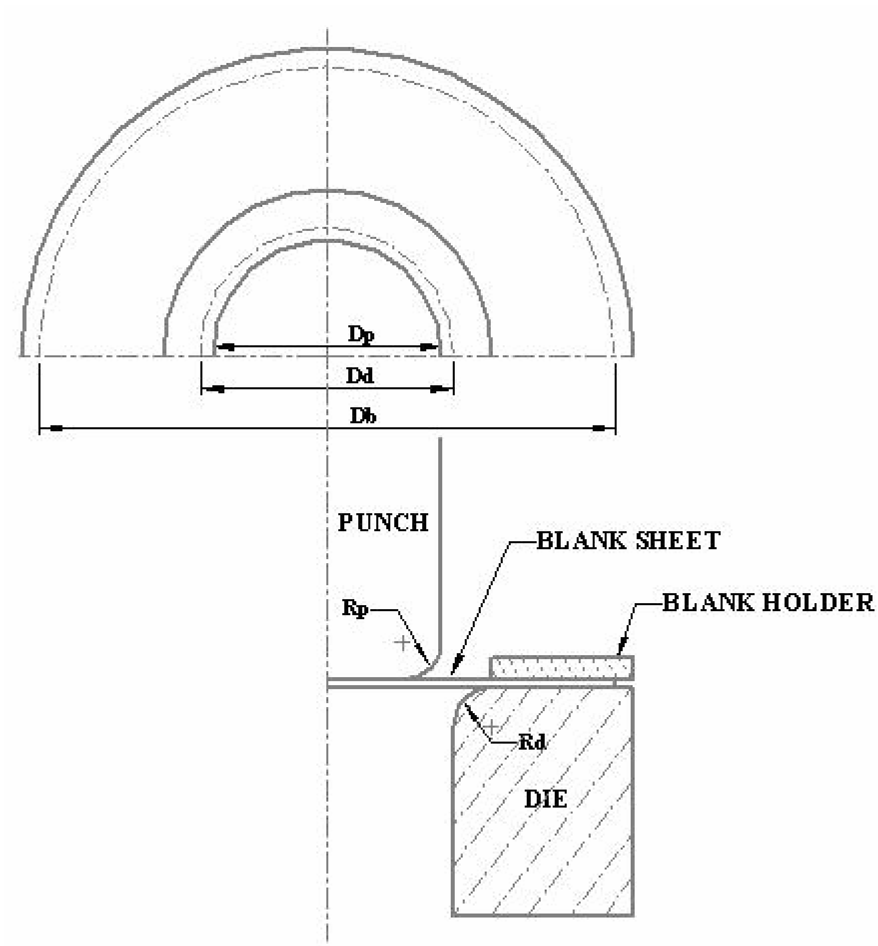
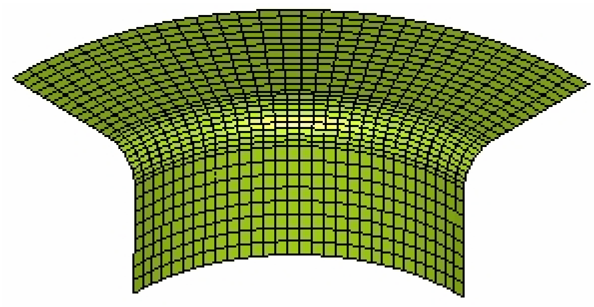


Fig. 21 Schematic diagram of the deep drawing process for a cylindrical cup

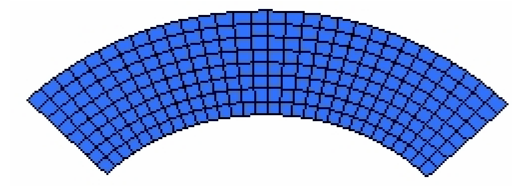
The tool dimensions and the process parameters used in the simulation of deep drawing process of a cylindrical cup have been shown in Table 4. The exploded view of the finite element mesh is shown in Fig. 22.

Table 4
Tool dimensions and the process parameters used in the simulation of deep drawing process of a cylindrical cup

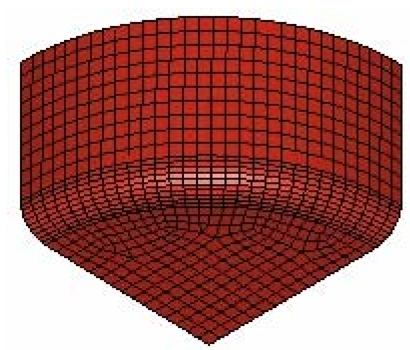
Parameter	*Value*
Punch velocity(mm/s)	20.0E+03
Blank holder force(KN)	12.0
Blank thickness(mm)	0.84
Diameter of punch, D_P(mm)	90.0
Diameter of die, D_d(mm)	93.5
Punch profile radius, R_p(mm)	6.00
Die profile radius, R_d(mm)	8.00
Cup height(mm)	35.0



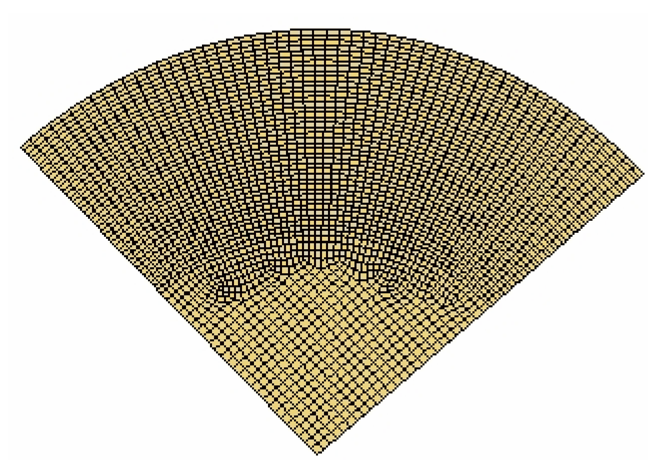
Die



Blank holder



Punch



Blank

Fig. 22 Exploded view of FE mesh for deep drawing process of cylindrical cup

Deformation analysis of the cylindrical cup is conducted exactly on the same lines as of square cup. The position of various stages set for the multi stage analysis is shown in Fig. 23. The final stage has a uniform trimming allowance of 0.75mm at the flange for a depth of 35mm.The shape error allowance is taken as 0.25mm. Initial circular blank of diameter of 80.98mm, found by line analysis technique, has been taken to start with the process.

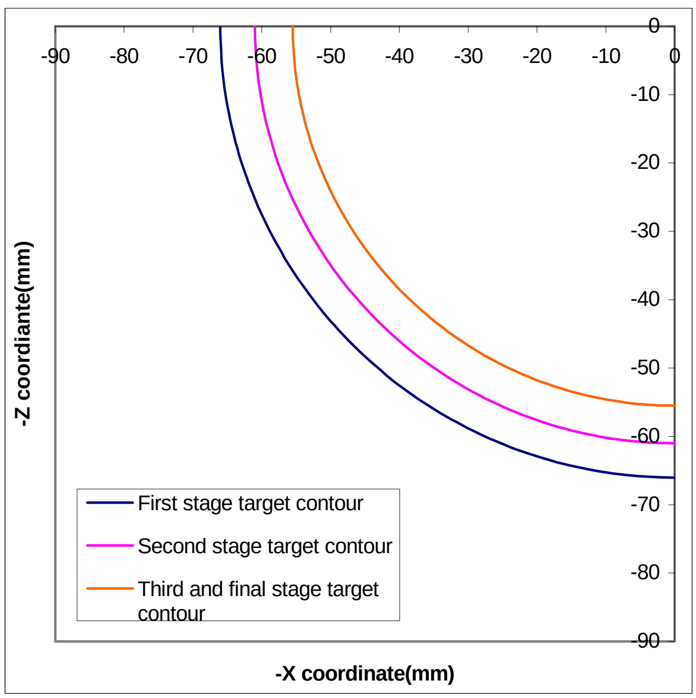


Fig. 23 Diagram showing position of stages for cylindrical cup

The progression of deformation analysis for multi stage is shown in Fig. 24.

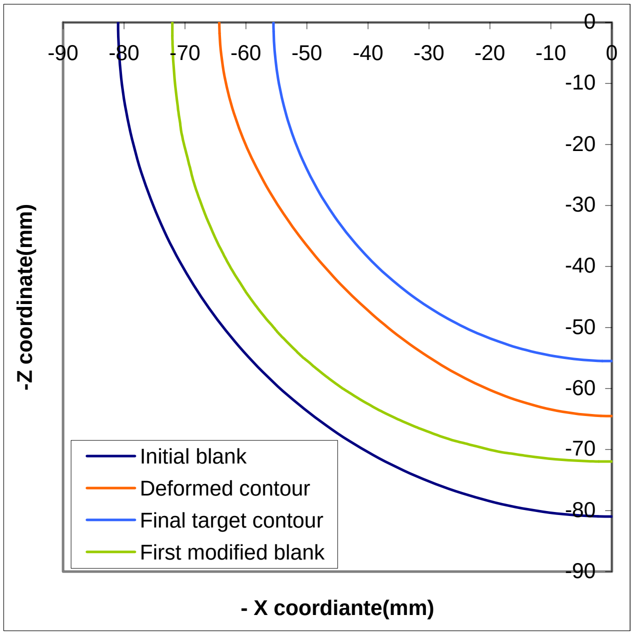


Fig. 24 Progression towards obtaining an optimal blank shape for a cylindrical cup using multiple stage analysis
(a) First iteration- Zeroth stage

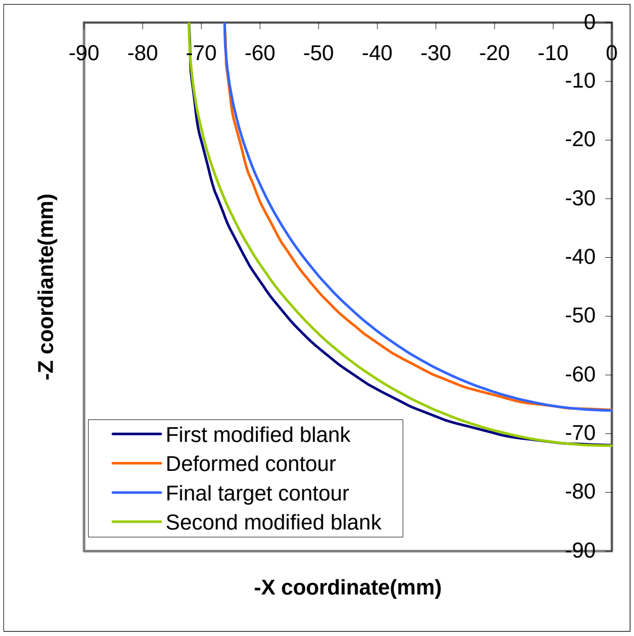


Fig. 24(b) Second iteration- First stage (Run 1)

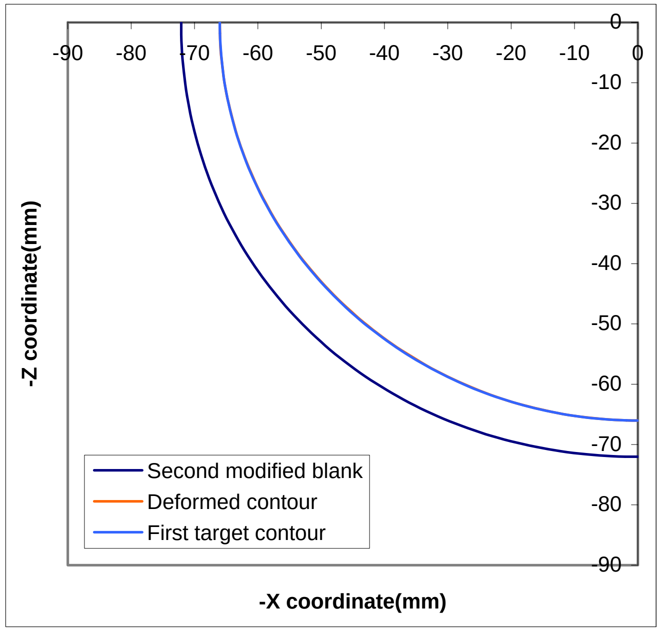


Fig. 24(c) Third iteration- First stage (Run 2)

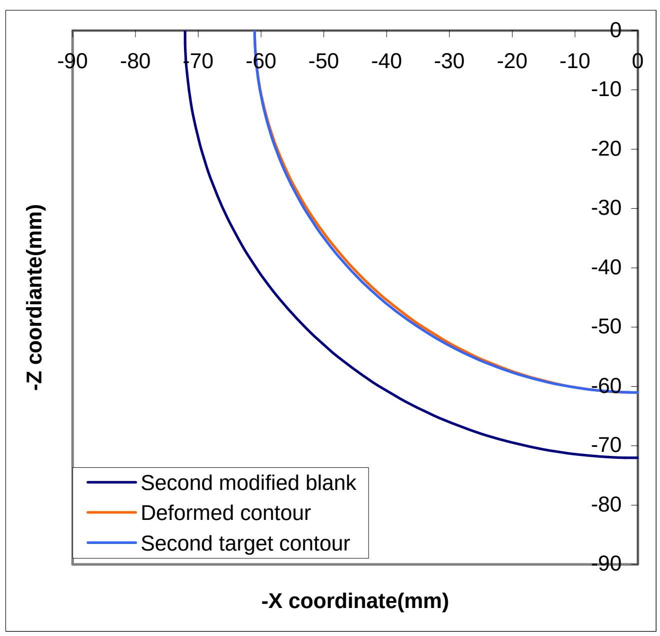


Fig. 24(d) Fourth iteration- Second stage (Run 1)

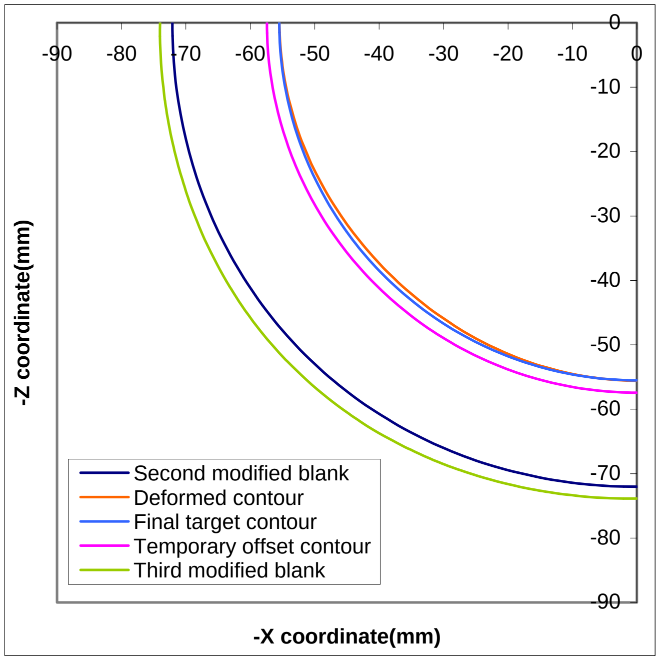


Fig. 24(e) Fifth iteration- Third stage (Run 1)

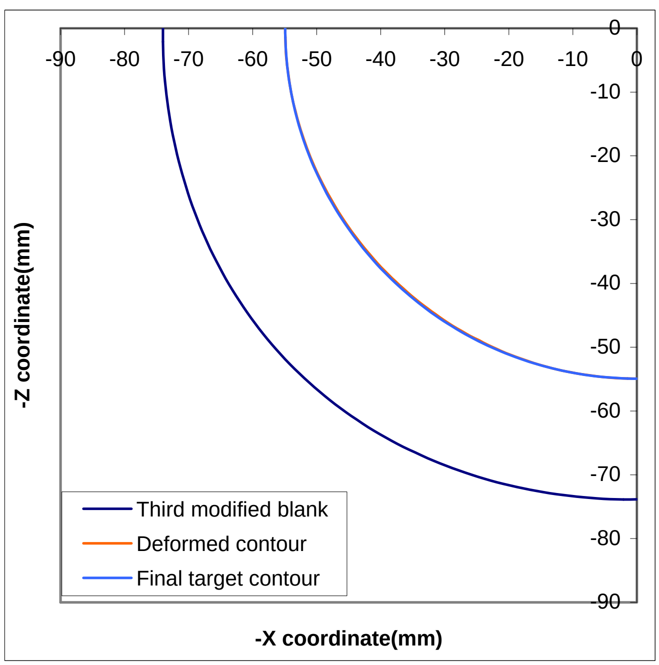


Fig. 24(f) Sixth iteration- Third stage (Run 2)

The third modified blank is the optimal blank shape for the cylindrical cup with shape error of 0.08mm. (shown in Fig. 25)

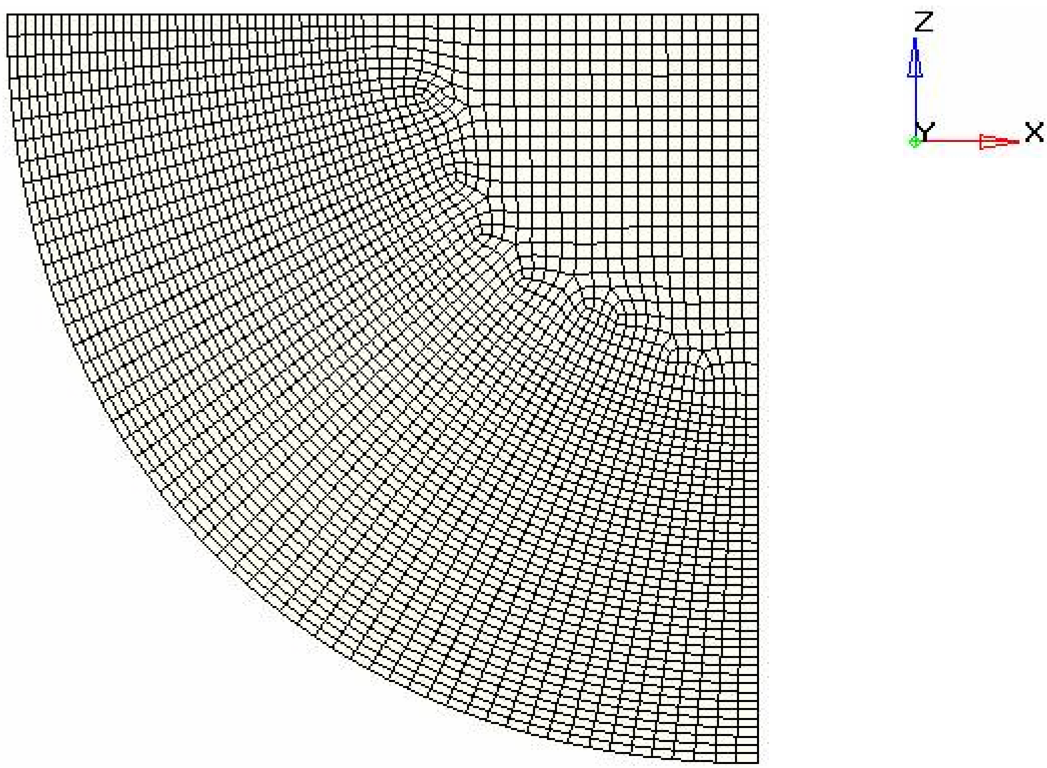


Fig. 25 FE mesh of optimal blank shape for cylindrical cup

The final shape of the flange obtained as a result of the deformation of the optimal blank shape up to a depth of 35mm is shown in Fig. 26.

The whole process takes a total of six iterations and three modifications to reach to the optimal blank shape. The progression of shape error through all the iterations is shown in Fig. 27.

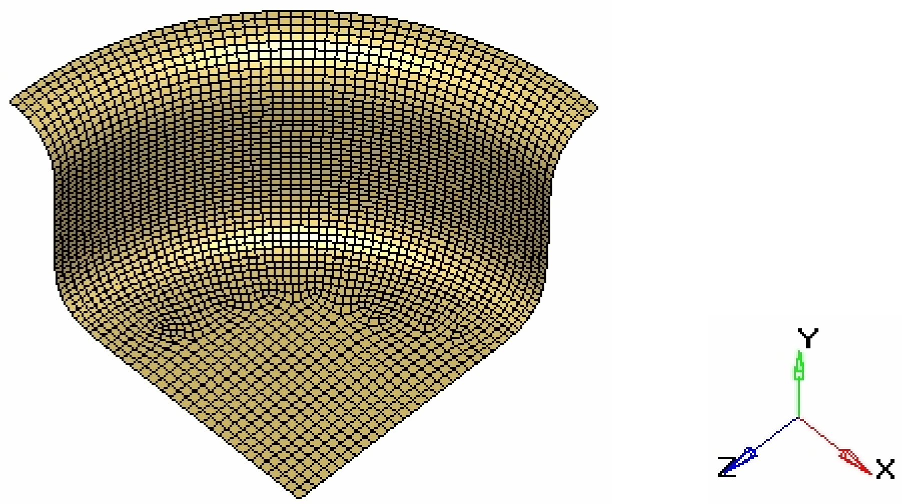


Fig. 26 Deformed shape of the optimal blank of a cylindrical cup

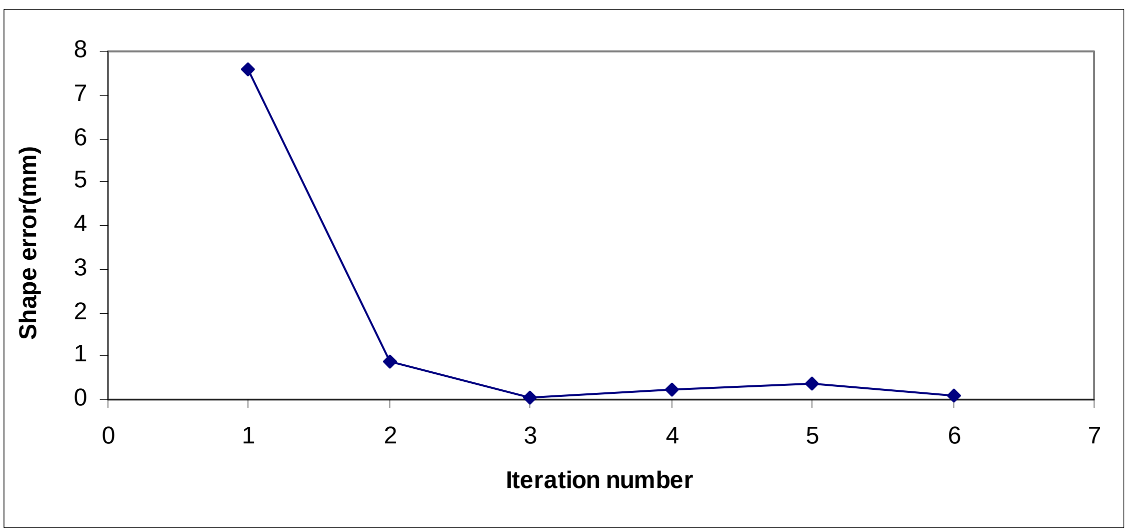


Fig. 27 Shape error history through all the iterations for a square cup using multiple stage analysis

The deformation analysis for single stage is shown in Fig. 28.

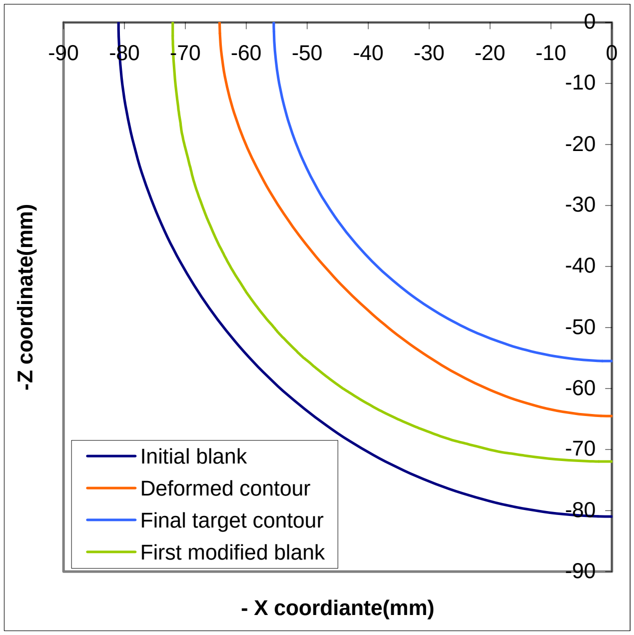


Fig. 28 Progression towards obtaining an optimal blank shape for a cylindrical cup using single stage analysis
(a) First iteration

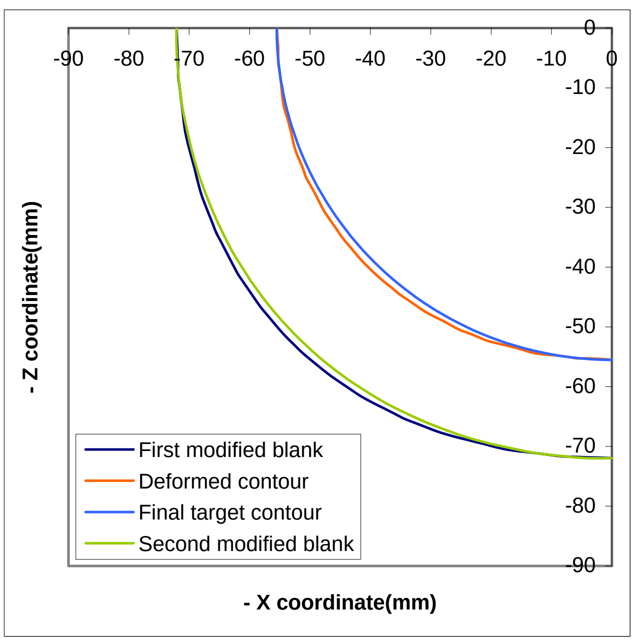


Fig. 28(b) Second iteration

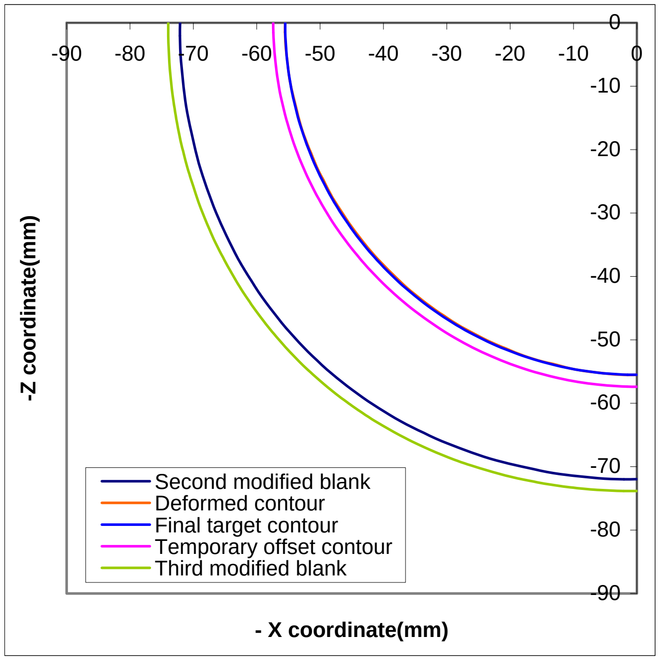


Fig. 28(c) Third iteration

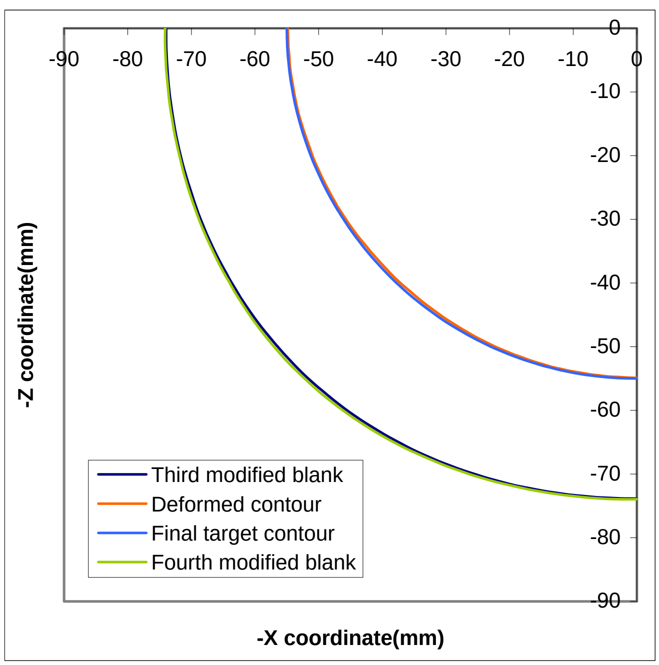


Fig. 28(d) Fourth iteration

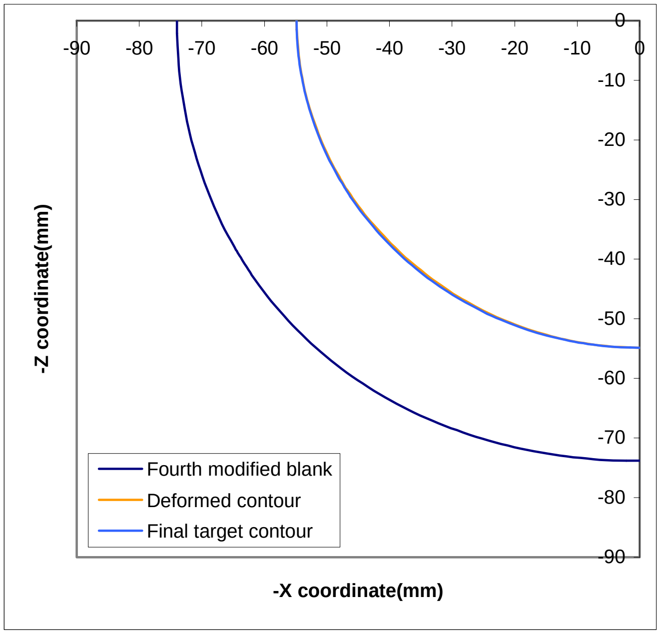


Fig. 28(e) Fifth iteration

It takes a total of five iterations and four modifications to reach to the optimal blank shape. The final shape error has been found to be 0.13mm.The progression of shape error history through all the iterations is shown in Fig. 29.

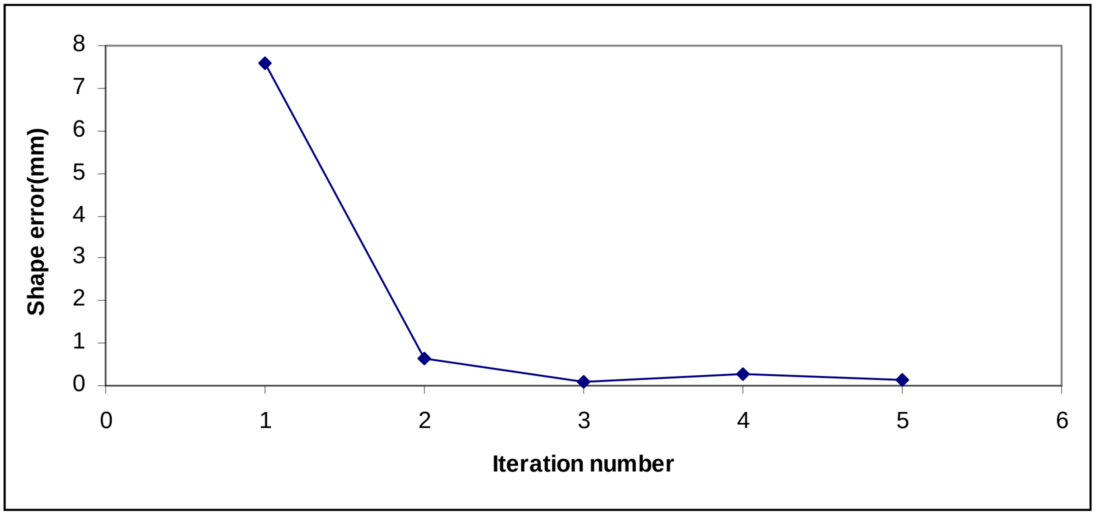


Fig. 29 Shape error history through all the iterations for a cylindrical cup using single stage analysis

The results of each iteration for single stage as well as for multi stage analysis in terms of shape error and CPU time cost are summarized in Table 5.

Table 5
Shape error and CPU time history in progression of optimal blank design for cylindrical cup undergone single stage and multiple stage analysis.

Iteration No.	For n = 3		For n =1	
	Shape error	CPU time	Shape error	CPU time
1	7.60	13m 15s	7.60	13m 15s
2	0.89	5m 33s	0.64	10m 48s
3	0.04	5m 36s	0.10	9m 34s
4	0.24	7m 38s	0.27	11m 27s
5	0.39	9m 16s	0.13	11m 51s
6	0.08	11m 58s		
Total time	53m 16s		56m 55s	

CHAPTER IV

INFLUENCE OF PROCESS PARAMETERS AND MATERIAL PROPERTIES

The blank material properties, such as yield strength, anisotropic behaviour, strain hardening exponent and process parameters such as friction, blank holder force, die profile radius, punch corner radius, etc., play a vital role in deciding the optimized blank size and shape to achieve the required shape of the cup of a particular depth. Even a change in the value of one of these parameters can result in different blank shape and size.

To study the effect of material properties and process parameters, simulation of deep drawing process for square cup have been carried out considering different anisotropic values, coefficient of friction and blank holder force.

4.1 Effect of coefficient of friction

The coefficients of static and dynamic friction between all the surface pairs are specified to be of the same value. Simulations have been carried out taking different values of coefficient of friction of 0.10, 0.15 and 0.20 and optimized blank achieved as a result of each of them are compared. The contours of different blank shapes achieved are plotted in Fig. 30. It has been found here that with the increase in friction there is very little effect on the shape and size of the blank. The change is due to the reason that with the increase of the friction more stretching of the blank takes place.

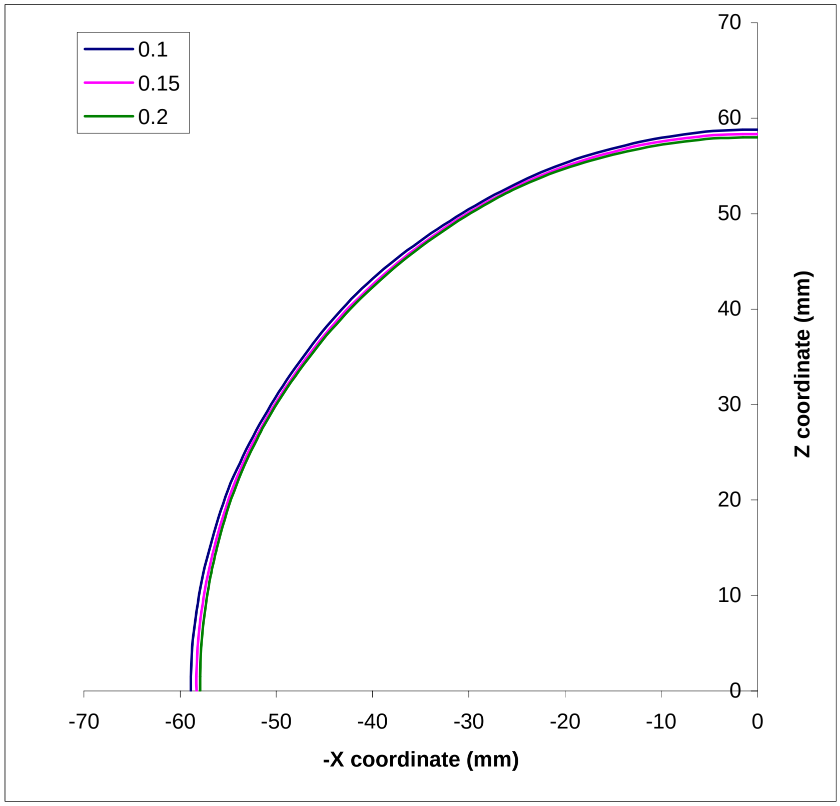


Fig. 30 Effect of friction

Thus increase of friction can be considered useful to reduce the blank size to some extent but on the other hand it may result in punch out failure at the bottom radius of the cup. Moreover, increase of friction will require more work to overcome friction.

4.2 Effect of blank holder force

Blank holder force helps in preventing wrinkling of the flange and to maintain the smooth flow of the material. Simulations have been carried out by taking different values of blank holder force of 12KN, 16 KN and 20KN. The different blank shapes achieved are plotted in Fig. 31. Results shows that change in blank holder force mainly affects the size of the blank and the shape of the blank is affected to a very less extent.

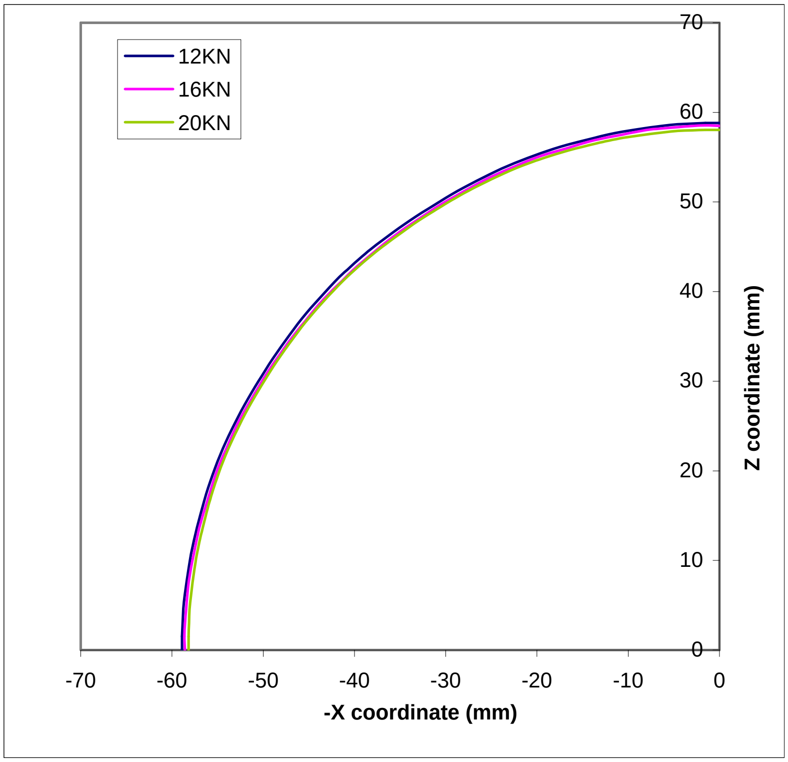


Fig. 31 Effect of blank holder force

Flange friction increases with increase in blank holder force so the force should be just sufficient enough to prevent wrinkling. Optimum blank holder force required decreases with increase in thickness to diameter ratio. For very thin sheets the blank holder force necessary to prevent wrinkling is so large that the increased friction lowers the limiting drawing ratio [40].

4.3 Effect of anisotropy

Lower R value indicates easy thinning and larger R value indicates resistance to thinning. Material flow considerably depends on anisotropic values and thus it becomes a crucial parameter. Simulations have been carried out by taking different R-values, as listed in Table 6. The different blank shapes achieved are plotted in Fig. 32.

Table 6
Anisotropic values

Case no.	R -values		
	R_{00}	R_{45}	R_{90}
1	2.15	1.78	2.43
2	1.00	1.00	1.00
3	0.70	2.50	1.20

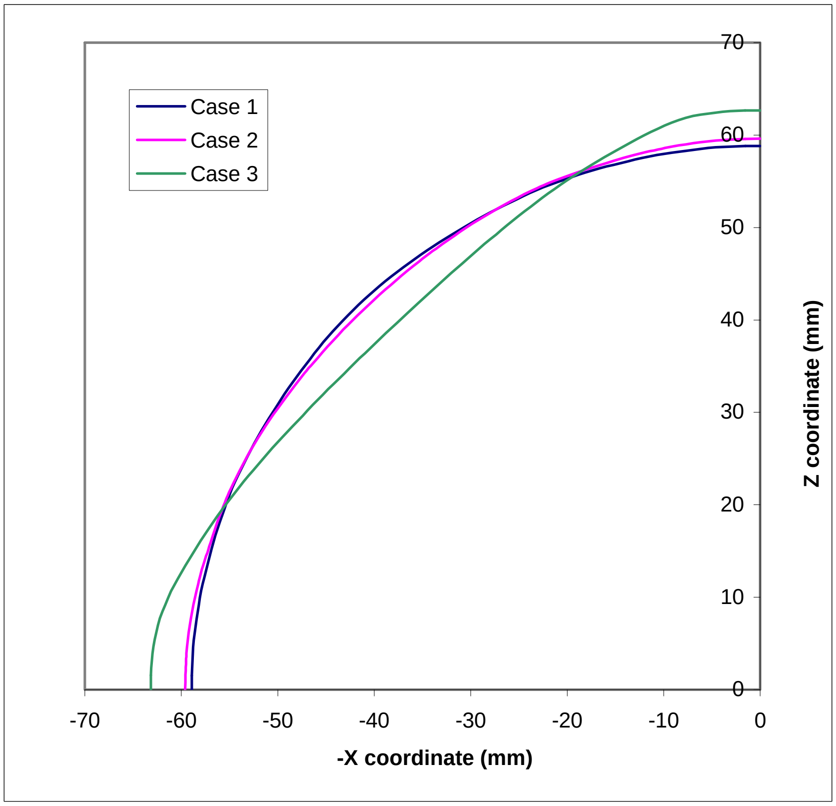


Fig. 32 Effect of anisotropy

It has been observed here that the change in anisotropy property changes both the size and the shape of the blank. This is clear from the plot of case 3 that larger R-value indicates restricted material flow in that direction as compare to the direction having lower R-value. Since the material in case 3 has got lower R-values in the 0° and 90° direction as compare to 45° direction, that is why optimum blank profile is shorter in the 45° direction as compare to 0° and 90° direction.

CHAPTER V

CONCLUSIONS

A simple and very effective method has been proposed to find the optimal blank shape design for deep drawing of arbitrary shaped cups having a uniform trimming allowance at the flange. The method is implemented using finite element modeling of sheet metal forming process which helps in achieving the deformed shape of the blank. To start the blank optimization process, the initial shape of the blank is found using line analysis technique. The iterative process is used to arrive at the optimum blank shape. A shape error is measured by comparing the deformed contour of the blank and target contour and is used to decide whether the deformed blank needs to be modified or not. The deformed blank is repeatedly modified until the deformed contour of the blank becomes almost coincident with the target shape. The proposed method has been practiced in single stage as well as in multiple stages. Examples of square cup and cylindrical cup have been investigated to examine the effectiveness of the proposed approach. Both examples involve fairly significant levels of planar anisotropy in the blanks. The simulation results provide excellent prediction of optimal blank shape for both the square cup and cylindrical cup in both single stage and multiple stage analysis. Since it takes less computational time in multiple stage analysis as compared to single stage analysis for prediction of the optimal blank shape, so the proposed method integrated with multiple stage analysis has been found as an effective tool for optimal blank design.

The present work is all about simulation so the experiments can be done to obtain the desired product from the optimal blank obtained by the proposed method. The present method can be further applied to optimum blank design of other practical stamping applications.

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APPENDIX A

SIMULATION OF DEEP DRAWING USING LS-DYNA

The finite element simulation was carried out on LS-DYNA. The pre-processing was done on HYPERMESH. Post-processing was done on HYPERVIEW. The rigid tooling of deep drawing consists of (1) Die (2) Blank holder and (3) Punch. The entire pre-processing process can be divided into six steps:

1. Creating geometry
2. Creating collectors
3. Meshing
4. Applying boundary condition
5. Updating cards
6. Control cards

1 Creating geometry

The geometry of the model is constructed using 3D CAD software *SolidWorks.* The model consists of four parts:

a) Punch

b) Blank holder

c) Blank

d) Die

Due to shape symmetry and in order to save the CPU time, only a quarter part of the model is constructed. The geometry file is saved in the IGES format that is later on imported in the HYPERMESH for further pre-processing.

2 Creating collectors

Four types of collectors were created:

a) Material

b) Property

c) Component

d) Load

2.1 Material collector (*MAT)

Material collector assigns the material property to the part. Since deep drawing consists of total four parts (3 rigid parts and blank), 4 material collectors were created. All the collectors are named according to the part. All the rigid tooling are specified *MAT_RIGID (MAT 20) which is the default rigid material for LS-DYNA. Blank is assigned *MAT_ANISOTROPIC_PLASTIC (MAT 103).

2.2 Component Collector (*PART)

Four component collectors are created and corresponding materials are assigned to each of them.

a) Die- Rigid

b) Punch- Rigid

c) Blank holder- Rigid

d) Blank- Anisotropic plastic material

2.3 Property Collector (*SECTION_SHELL)

A shell section is created that is assigned to all the parts.

2.4 Load Collector (*BOUNDARY_PRESCRIBED_MOTION_RIGID AND LOAD_RIGID_BODY)

One load collector for axial punch movement and one for axial force on the blank holder are created.

3 Meshing

Before starting to mesh any part, it is important to select the collector corresponding to the part to be meshed from the global menu. By this all the nodes and the elements that are to be created will be automatically assigned the property of that component. Meshing of the model is done using automesh feature in 2d panel employing quadrilateral elements.

4 Boundary Condition

4.1 Contact

For defining the contact between different surface pairs, the option "CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE" is used. The surface pairs are blank-blank holder surface, blank-punch surface and blank–die surface. The Contact option is specified by selecting master surface and slave surface. The rigid part is always selected as the master surface and the blank (which is finely meshed) is always selected as the slave surface. The coefficients of static and dynamic friction between all the surface pairs are specified to be same of the value of 0.10.

4.2 Blank holder force

A force of constant magnitude of 20KN is applied on the blank holder in the axial *y*-direction. This will help in preventing wrinkling and to ensure the smooth flow of sheet metal on the die lip during the deformation process.

4.3 Checking penetration

Penetration option from the *Tool* page was selected. Penetration check was done for the specified contact interface. To avoid penetration two things have to be kept in mind; the normal of the contact pairs should be opposite to each other. If both the normals point towards each other then normal of one of the surface has to be reversed from the normal menu on the *Tool* page. The slave surface (blank) should have a finer mesh than the master surface (rigid part). If there is penetration then the element size of the blank needs to be decreased.

5 Updating cards

This is the last step in creating the input deck.

5.1 Mat collector

We have two materials, one for the blank and one for the rigid tooling. For the rigid tooling, only three material properties are specified: Young’s modulus, Mass density and poison’s ratio. For the blank material, besides these properties value of initial yield stress, Lankford coefficients and stress-strain relation are also specified. It is essential that units should be consistent because LS-DYNA does not have in built unit. The other important thing that was specified is the translational and the rotational constraint of the rigid bodies.

5.1.1 Die

Die was constrained in all translational as well as rotational degrees of freedoms.

5.1.2 Punch and Blank holder

Punch and blank holder are constrained for *x* and *z* translation and rotations in all the three axes. Only displacement in *y*- direction is allowed for both of them.

5.1.3 Blank

Since only quarter model of the blank is constructed, it was necessary to constraint the blank according to symmetric boundary conditions.

5.2 Property Collector

Shell element, thickness and NIP (number of integration points) are specified for the shell segment. Four noded, Belytschko-Tsay elements with 5 NIP having a thickness of 0.84mm is specified for each part.

5.3 Component Collector

Material and section property is applied to the component (*PART) in this.

5.4 Load collector

The translation of the punch is specified using *BOUNDARY_PRESCRIBED_MOTION_RIGID. Displacement boundary condition and load curve is defined. The load curve defines the displacement of the punch with respect to time.

The force on the blank holder is specified using LOAD_RIGID_BODY. Load curve is defined which specifies the constant blank holder force with respect to time.

6 Control cards

At the end control cards were added. Using these cards the termination time, shell property, contact property and data base plots are defined.

APPENDIX B

COMPUTER PROGRAM IN MATLAB TO FIND THE MODIFIED CONTOUR OF THE BLANK

```
% “main_prog.m” Function
% This program calculates the supposed position of the nodes on the target contour
% Input file is ‘ input.xls ’ that has got the coordinates of the nodes of the
% deformed contour and one deformation step before the deformed contour
% Run command is [X2,Z2]= main_prog(m)
% where ‘ m’ is the position of the target contour on x-axis or z-axis
% Other functions that it calls are ‘assign’, ‘assign1’, ‘assign2’, ‘solve_g3’ and
% ‘solve_g4’
% Output file from this program is ‘out_node.txt’
% WRITTEN BY
% AMIT GOEL, DEC. 2004

function[X2,Z2]= main_prog(m)
A= xlsread('input.xls');
[rows,cols]=size(A);
F_Out = fopen('out_node.txt','w')
for i=1:rows
   node_name=A(i,1);
   x1=A(i,2);
   x2=A(i,3);
   z1=A(i,4);
   z2=A(i,5);
   syms x z
   eq1=(x-x1)*(z2-z1)-(x2-x1)*(z-z1);
   eq2=x+m;
   eq3=z-(12.5+(-1.*x^2-25.*x+m^2-25.*m)^(1/2));
   eq4=z-m;
   g2=solve(eq1,eq2);
   try
      g2.x;
      g2.z;
      if (double(g2.z)>=-2) & (double(g2.z)<=12.5)
         [X2,Z2] = assign(g2);
      else
         [X2,Z2] = solve_g4(eq1,eq2,eq3,eq4,x,z,m);
      end;
```

```
   catch
      [X2,Z2] = solve_g4(eq1,eq2,eq3,eq4,x,z,m);
   end;
   supp_x = double(X2);
   supp_z = double(Z2);
   fprintf(F_Out,'%i   ',node_name);
   fprintf(F_Out,'%6.4e  %6.4e',x1,supp_x);
   fprintf(F_Out,'    %6.4e  %6.4e\n',z1,supp_z);
end
fclose(F_Out);
```

% “solve_g3.m” Function

```
function[a,b] = solve_g3(eq1,eq2,eq3,eq4,x,z,m)
g3=solve(eq1,eq3);
try
   g3.x;
   trial1=double(g3.x);
   g3.z;
   trial2=double(g3.z);
   if (trial1(1)>=-m) & (trial1(1)<=-12.5) & (trial2(1)>=12.5) & (trial2(1)<=m)
      [a,b] = assign1(trial1,trial2);
   else
      try
         trial1(2);
         trial2(2);
         if (trial1(2)>=-m) & (trial1(2)<=-12.5) & (trial2(2)>=12.5) & (trial2(2)<=m)
            [a,b] = assign2(trial1,trial2);
         else
            a=0;
            b=0;
         end
      catch
         a=0;
         b=0;
         disp 'out of range'
      end;
   end;
catch
   a=0;
   b=0;
   disp 'does not intersect'
end;
```

% “solve_g4.m” Function

```
function[a,b] = solve_g4(eq1,eq2,eq3,eq4,x,z,m)
g4=solve(eq1,eq4);
try
   g4.x;
   g4.z;
   if (double(g4.x)>=-12.5) & (double(g4.x)<=2)
      [a,b] = assign(g4);
   else
      [a,b] = solve_g3(eq1,eq2,eq3,eq4,x,z,m);
   end
catch
   [a,b] = solve_g3(eq1,eq2,eq3,eq4,x,z,m);
end;
```

% “assign.m” Function

```
function[a,b]=assign(g)
a = g.x;
b = g.z;
```

% “assign1.m” Function

```
function[a,b] = assign1(trial1,trial2)
a = trial1(1);
b = trial2(1);
```

% “assign2.m” Function

```
function[a,b] = assign2(trial1,trial2)
a = trial1(2);
b = trial2(2);
```

% “shape_err.m” Function
% This program calculates the shape error
% It takes ‘out_node.xls’, the output file from the ‘main_prog’, as the input file
% Run command is [shape]=shape_err
% Output file from this program is ‘out_scale_error.txt’

```
function[shape]=shape_err;
A= xlsread('out_node.xls');
[rows,cols]=size(A)
syms d;
d=zeros(rows,1);
F_Out = fopen('out_scale_error.txt','w');
for i=1:rows
   node_name=A(i,1);
   x1=A(i,2);
   x2=A(i,3);
   z1=A(i,4);
   z2=A(i,5);
   d(i,1)=sqrt((x2-x1)^2+(z2-z1)^2);
   out_d=double(d(i,1));
   fprintf(F_Out,'%i   ',node_name);
   fprintf(F_Out,' %10.4e\n',out_d);
end;
shape_error=mean(d)
fprintf(F_Out,'\n\n  ');
fprintf(F_Out,'SHAPE ERROR =');
fprintf(F_Out,'%6.2f',shape_error);
fclose(F_Out);
```

% “Final.m” Function
% This program calculates the coordinates of the nodes of the deformed contour
% It takes two input files: ‘ initial_one.xls’ and ‘out_node.xls’
% The file ‘initial_one.xls’ contains the coordinates of the nodes of the initial
% contour of the blank and after first deformation step. ‘out_node.xls’ is the
% output file of the ‘main_prog’.
% Run command is [X2,Z2]=final
% Output file from this program is ‘out_final_node.txt’

```
function[X2,Z2]=final
A= xlsread('out_node.xls');
B= xlsread('initial_one.xls');
[rows,cols]=size(A);
syms x z d;
d=zeros(rows,1);
F_Out = fopen('out_final_node.txt','w');
for i=1:rows
   node_name=A(i,1);
   x1=A(i,2);
   x2=A(i,3);
   z1=A(i,4);
   z2=A(i,5);
   x3=B(i,2);
   x4=B(i,3);
   z3=B(i,4);
   z4=B(i,5);
   eq5=(x-x3)*(z4-z3)-(x4-x3)*(z-z3);
   d(i,1)=sqrt((x2-x1)^2+(z2-z1)^2);
   out_d=double(d(i,1));
   eq6=(out_d)^2-((x-x3)^2+(z-z3)^2);
   fin=solve(eq5,eq6);
   xx=double(fin.x);
   zz=double(fin.z);

   if(x1<=x2 & z1>=z2)
      a=max(xx);
      b=min(zz);
   else

      a=min(xx);
      b=max(zz);

   end
```

```
    fprintf(F_Out,'    %i        ',node_name);
    fprintf(F_Out,' %6.4f    %6.4f    ',x3,a);
    fprintf(F_Out,' %6.4f    %6.4f    ',z3,b);
    fprintf(F_Out,' %6.4f    %6.4f    %6.4f    %6.4f',x1,x2,z1,z2);
    fprintf(F_Out,' %10.2f\n',out_d);
end;
fclose(F_Out);
```

APPENDIX C

GRAPHICAL METHOD TO FIND THE INITIAL BLANK GEOMETRY

The graphical method [41] is considered more suitable for drawing of rectangular cups. To start the layout for the blank, a rectangle ABCD is drawn as shown in Fig. 33 having side dimension (x-2r) is drawn where x, r are the side and bottom corner radius, respectively, of the required square cup. By continuing the sides beyond the points A, B, C, D, for a length equal to h+1.57r, where h is the height of the flat portion of the sides of the finished shell, and connecting the points by lines parallel to the outline of the original rectangle, the outline of a shell blank is obtained where bending only is done during the drawing operation. To this outline add the quadrants with a radius equal to R_c. The value of R_c is obtained by the equation (a):

$$R_c = (2Rh + R^2 + 1.41Rr)^{1/2} \tag{a}$$

where

R= corner radius

h = height of flat portion of sides

r = bottom radius

Theoretically, this blank outline contains enough metal to draw the shell. Because the blank has sharp corners, slits, folds, and overlaps will occur at the points where the quadrants meet the side walls when the shell is drawn. The sharp corners must be blended by sloping curves by taking the metal from the side walls and adding it to the quadrants without any change in the amount of metal in the blank.

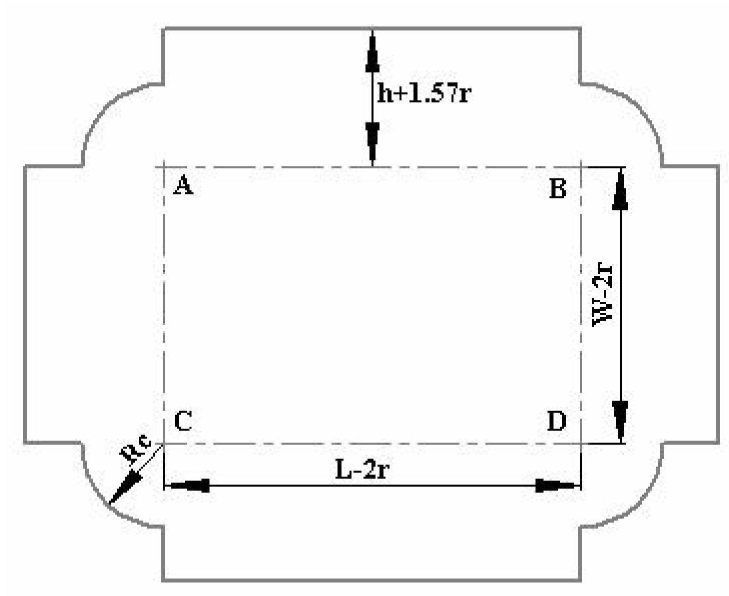

Fig. 33 Layout of a blank for a rectangular shell

The method for blending the corners of rectangular blanks by sloping curves is illustrated in Fig. 34. To develop the corners, proceed thus:

1. Bisect *ab* and *cd*. Through the dividing points *e* and *f*, respectively, draw *gh* and *ij* tangent to the quadrant arc.
2. Draw the arcs with a radius R_c which will touch the outer edges of the side walls and the tangents *gh* and *ij*.

The development of the blank corners in this manner assures even distribution of the metal because the areas of the shaded curvilinear triangles outside the sloping curves in the side wall are equal to the areas of similar triangles added to the quadrant arcs inside the sloping curve.

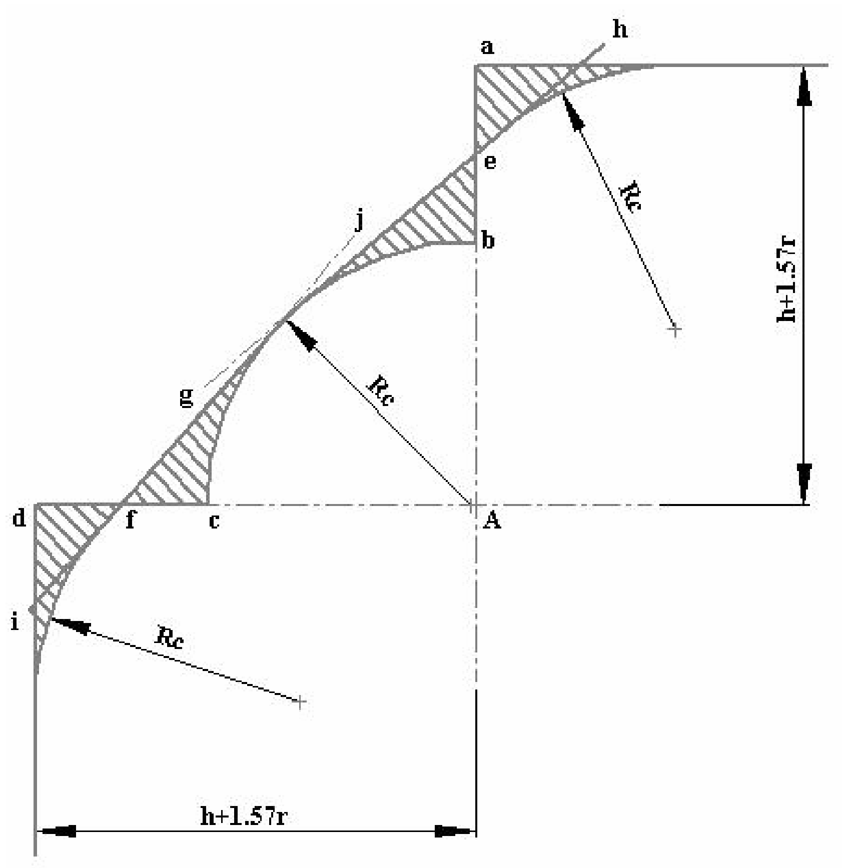

Fig. 34 Corner development of blanks for rectangular draws

VITA

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